FAST ALGORITHM FOR VOLTAGE CONTINGENCY SELECTION

A Thesis Submitted

in Partial Fulfilment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

by

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to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

June, 1992

CERTIFICATE

Certified that the work entitled 'FAST ALGORITHM FOR VOLTAGE CONTINGENCY SELECTION' being submitted by Mr. M. VENKATESWARA RAO Roll No. 9020404, in partial fulfilment of the award of degree of Master of Technology, has been carried out under our supervision. To the best of our knowledge, this thesis dessertation has not been submitted elsewhere for the award of a degree.

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ABSTRACT

This thesis is addressed to the development of fast and efficient methods for voltage contingency selection. One of the problems faced in the real time execution of security analysis, especially the voltage security analysis, is the non-availability of fast and accurate methods for predicting the post outage conditions. Hence, the attempts have been made in this thesis to suggest a new set of voltage and reactive power distribution factors which can be used for rapid computation of the post outage system states with sufficient accuracy.

Another difficulty is due to non-availability of proper performance indices which will reflect the true relative severities of contingencies. Various contingency ranking methods available in literature, in general, suffer from the masking and misranking effects. To overcome these problems, several new higher order performance indices have been explored. A simple approach, based on least square error minimization, to compute the optimal values of weights associated with voltage and reactive power performance indices has been suggested.

The potential of the proposed distribution factor based model and the new performance indices for voltage contingency selection have been tested on IEEE-14 bus and a 19 bus Indian system.

DEDICATED TO

MY PARENTS AND AUNT

ACKNOWLEDGEMENTS

With profound sense of gratitude I express my sincere thanks gurus and guides Dr.S.C.Srivastava and Dr.P.K.Kalra for suggestin topic and guiding me throughout course of the thesis work. My have been the constant source of inspiration and encourageme times when I was passing through difficult moments.My special are due to Dr.S.C.Srivastava for sparing his valuable time to com the thesis work in-time.

I am grateful to Dr.L.P.Singh, Dr.R.Arora, Dr.S.S. Dr.R.K.Varma, and Dr.P.R.K.Rao for teaching me various adv courses during my M.Tech. I would like to express my hear thanks to Mrs (Dr.) Damayanti Singh for teaching me the adv features of English language.

I am fortunate to be in the splendid company of Mahendra, Prasad, and Chandra Shekar in particular and all H-top Junt generale during my stay here. My alter ego Ved needs a sp mention for he being my Hindi guru.

My special thanks are due to K.N.Srivastava for the val discussions we had during our course work and thesis work. grateful to S.N.Singh for providing me UPSEB data and it's det I am thankful to my Doordarshan friends, Defence friends and a my friends who involved directly or indirectly in thesis prepar and gave me good company in the campus.

I am indebted to Capt. Rajeev Sawhney and his family Dr.N.N.Kishore and his family who made my stay at IIT K memorable

I am also thankful to Mr. Bajpai for his fast and efficient writing.

----Rao

CONTENTS

CHAPTER - 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Security is a term used to reflect a power system's ability to meet its loads without unduly stressing its apparatus or allowing network variables to stray from prescribed ranges. Of particular concern are the sudden changes or disturbances in the system. The framework normally used to examine the security of the power system network is based on its probable transition of operating states following a disturbance or contingency.

The power system is thought of as being run under two sets of constraints : load and operating. The load constraints impose the requirements that all loads be met, the operating constraints impose lower and upper limits on network variables. The system states have been broadly classified as Normal, Emergency and Restorative states. The system is in the 'normal state' when the load and operating constraints are met. The system is in 'emergency state' when there are violations of operating constraints, though satisfying load constraints. In 'restorative state' the system operating constraints are met but load constraints are not satisfied. Further detailed classification of states are reported in literature such as a five state model of Fink and Carlson [5].

Security is defined with respect to a set of random events called the 'set-of-next-contingencies'. This is collection of disturbances that could happen. A system is said to be secure if it is in the normal state and none of the contingencies could cause its transition to the emergency state. If all the possible contingencies in a power system network are considered, it can never achieve a 'secure' state. Hence, the security is referred only with respect to a certain prespecified credible contingencies whose probability of occurrence is high. These disturbances, are either in the form of 'network outages' such as a line or a transformer outage or in the form of 'power outages' e.g. a generator outage. Following these outages, the system becomes deficient of transmission and/or generation capabilities, causing the lines to be overloaded beyond its thermal or stability limit and bus voltage limits. These two violations viz. line flows and bus voltages are mainly related to the deficiency of real power flow and reactive power support respectively. Hence the two are studied as separated subproblems known as 'Line flow or MW Security' and 'Voltage security' studies. This thesis mainly concerns with the 'Voltage security' problem which has attracted the attention of researchers in the recent past.

Secure operation of power system requires the assessment of security with respect to the preselected set of contingencies and the planning of corrective control actions if it is found to be in 'insecure' state. The two major functions of power system security are i) Security assessment and ii) Security control.

Security analysis and control have been implemented through a number of software packages in modern energy control centers. The major components of on-line security analysis are shown in Fig. 1.1. The monitoring component starts with the real-time measurements of physical quantities such as line power flows, line current flows, power injections, and bus voltage magnitudes; as well as, the status of breakers and switches. The measurement data are telemetered from various locations to the control center computer. Bad measurement data are rejected by filtering the transmitted data through a simple check of their reasonability and consistency. The remaining data are first systematically processed to determine the system configuration (generator and transmission network connections) or network topology. Then the available data are further processed to obtain an estimate of the system state variables (bus voltage magnitudes and phase angle for normal steady-state). State estimation is a mathematical procedure for computing the "best" estimate of the state variables of the power system based on the available data, which are in general corrupted with errors.

To assess whether a normal operating state is secure or not, a set of contingencies are analyzed. Therefore, to assess the system response to contingencies, a contingency evaluation is carried out using the on-line load flows. The on-line load flow uses the actual load flow model of one's own system (from the state estimation solution) together with a system representation of the unmonitored network and neighbouring systems, i.e., an

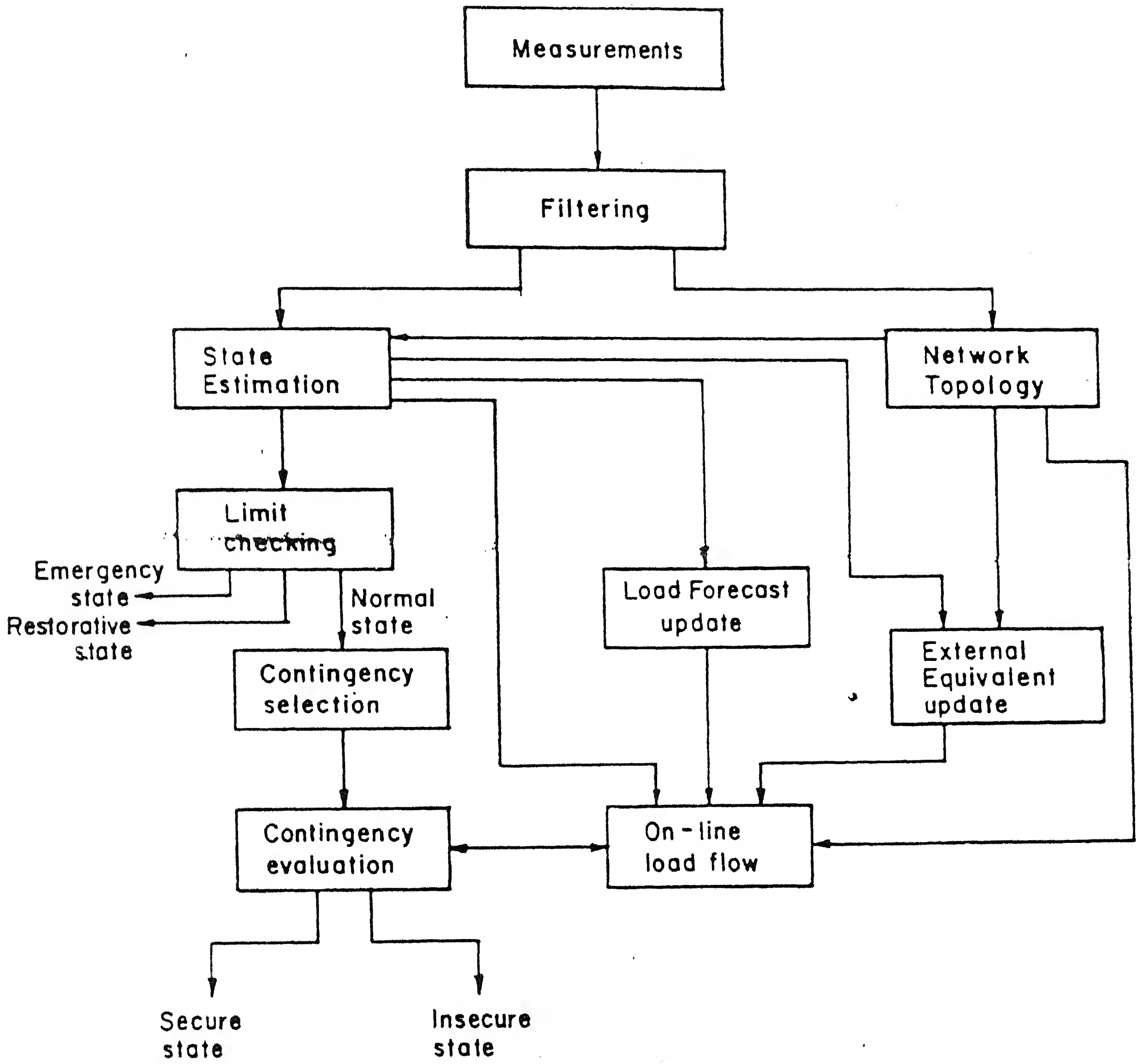

Fig.1.1 Security monitoring and analysis functions

external network model. Because the contingencies are future events, a bus load forecast is needed.

In a practical power system, the number of contingencies to be considered are so large that it is not possible to analyze all of them in real time requirement using on-line load flows based on full AC load flow models. Hence all the contingencies are first analyzed using some approximate load flow models or using precomputed distribution factors and ranked according to their severity. In order to assess the relative severity of the contingencies, scalar performance index is calculated for each of them which is function of the variables being monitored such as line flows in case of 'MW security' and bus voltage or reactive power injection in the case of 'Voltage Security'. The process of analyzing the contingencies using approximate models and ranking them according to their relative severities is known as "Contingency Selection". Once the contingencies are ranked according to their severity, the contingency analysis is performed using full AC load flow model starting from the most severe case, and stopping at a contingency which does not cause violation of operating constraints. With this two step procedure, normally a few contingencies are required to be analyzed by full AC load flows, thus reducing the time for security analysis. However, on-line security analysis has remained still a challenge to the power system researchers. Some of the desired features of a contingency selection algorithm are :

i) It should employ an extremely fast and sufficiently accurate method to compute the post outage state of the network for each of the contingencies.

ii) It should employ a ranking or screening method which accurately reflects the severity of the contingency cases.

1.2 STATE OF THE ART AND MOTIVATION

Power system security, being an important aspect of modern day power systems to achieve a high degree of reliable electric supply, has attracted researchers since past two decades and has created renewed interest in the recent past.

It is not possible to review the large number of literature available in the area of power system security. Hence a limited literature survey of the works related to the topic of the present thesis has only been carried out. Moreover, a recent paper by Balu et al. [30] provides the state of art in the area of power system security analysis and presents an overview.

In a practical large power system there can be thousands of credible contingencies. Keeping in view the enormous computational effort involved, the total number of contingencies must be reduced for detailed investigations. This is indeed the purpose of contingency selection. Contingency selection itself requires fast computational approach because of the need to study thousands of cases in a short span of time. The severity of an outage is indicated by the numerical value of the performance index PI, which is a function of the line overloads or bus voltage

deviations. Hence, linear, non-iterative approximate techniques have to be employed for such real time applications. Inverse matrix modification Lemma (IMML) [4] and compensation techniques have been presented in the literature for this purpose. For line or MW contingency ranking Generation shift distribution factors (GSDFs) and line outage distribution factors [1] are very popular because of their speed of solution.

G.C. Ejebe et al. have presented a fast technique for the automatic ranking and selection of contingency cases for a power system contingency analysis study [6]. A contingency list is built containing line and generator outages which are ranked according to their expected severity as reflected in voltage level degradation and circuit overloads. Besides this paper, many efficient and reliable algorithms were developed [8,9,13,21]. But most of these techniques can only be applied to MW limit security problems.

On the other hand, voltage problems also forms a very important aspect of security assessment. Many papers have been published in literature on voltage security assessment [7,10,12, 14,15,17,19].

If a contingency causes voltage problems, then, in may instances, these problems are in the neighbourhood of the dropped element. Utilizing this property, Zaborsky et al. developed a method [7] which uses a Gauss-seidel solution algorithm, starting the solution on buses near the outage, and expanding outward.

During the solution, voltage on buses near the outage are updated while the voltage on buses distant from the outage are assumed to be constant. As the solution continues, buses farther and farther from the outage have their voltages, until a point is reached where the changes are insignificant. Voltages of buses still farther from the contingency can be assumed to have remained constant. The drawback with this method is that the algorithm may overlook certain changes in bus voltages remote from the contingency.

Khu et al. [12] have reported a fast non-iterative linearization method devised to evaluate the effects of single or multiple-circuit contingencies upon the system laod-bus voltage. The standard DC load flow technique has been used to estimate the change in load-bus voltages due to the outage of one or more circuits. The authors also presented a method to calculate the reactive power change required to maintain scheduled voltages at generator buses. The method assumes as many as eight assumptions and some of them are not justified in a true power system network.

Lauby et al. [15] have compared the three methods of contingency selection - a performance index method, a local solution method, and a single iteration of the Stott-Alsac decoupled load flow. The authors observed that for large number of contingencies, the PI method which is a function of real flow in lines would be the fastest of the ranking methods. The method performs well in detecting widespread and severe voltage problems. However, the PI method is not well suited for the detection of

local problems. Overall the local solution method has been found to be well for selecting circuit outages. In fact it performed better than the single iteration of the decoupled load flow.

K. Nara et al. [17] have presented a new concept in formulating a performance index for contingency selection concerning voltage security analysis. The proposed performance index has the ability to select the severity of voltage limit violations. The infinite norm is used as a filtering algorithm to rank the contingencies in a paper published by Wasley et al. [14]. A method for evaluating the effectiveness of the presently automatic contingency algorithms in capturing contingencies which give out-of-limit conditions has been presented by Halpin et al. [16].

Stott et al. [18] presented various enhancements to the automatic contingency selection approach have shown how general ranking formulae can be extended to the multiple branch contingencies.

First time in the literature, Marija Illic-spong et al. have tried to develop a new formulation of distribution factors which is suitable for the analysis of the reactive power problem [20]. They used the S-E graph and its decoupled version Q-V graph to define the new distribution factors. Followed by their work Taylor et al. [28] have presented an algorithm that can be used in analysing reactive power flow contingencies. This approach uses the widely used MW distribution factors in conjunction with

another set of VAR distribution factors to solve interatively for the post-contingency bus voltage magnitude changes. But these algorithms [20,28] utilize iterative scheme and do not provide a set of distribution factors which can be used for direct calculation of post outage states. Recently, Lee and Chen [29] have presented a method to calculate set of distribution factors of reactive power flow for transmission line and transformer outage studies. The derivation of these distribution factors are based on fast decoupled load flow equations.

A fast security analysis technique for voltage security assessment has been presented in ref. [22] The method identifies the location of buses with potential voltage problems and thereby defines a voltage sensitive subnetwork for contingency screening. This allows the evaluation of large number of contingencies. V. Brandwajn et al. [23] have developed an efficient contingency screening method for detecting both branch MW flow violations and bus voltage limit violations. The efficiency of the method has been derived from bounding criterion which reduces the 1) number of branch-flow computations and limit checking, and 2) number of buses for which the Q-mismatch has to be calculated. The method is based upon the incremental angle criterion and the fast decoupled power flow.

A direct ranking algorithm for contingency selection taking into consideration voltage security problems has been presented by Chen and Bose [24]. In direct ranking, the second order PI for a contingency case is formulated in such a way that detailed

knowledge of post-contingency voltages at each individual bus is not necessary.

Schafer et al. [25] have presented a systematic analysis of masking effect in contingency selection and described a new concept with the aim to compensate for it. In this paper, the authors have introduced a vector norm based PI formulation, which allows a quantitative description of the masking effect. In ref. [25] a new algorithm has been presented for security analysis considering voltage security problems. The approch is based on a newly developed adaptive pre-filter. The authors used reduced models for both contingency selection and analysis.

Schafer et al. [27] have presented an expert system based novel approach for contingency selection [27]. To avoid the masking effect which is common in algorithmic contingency selection methods the expert system CONTEX incorporates operator knowledge into the contingency selection process.

From the limited literature survey presented above it is found that most of the papers on voltage contingency selection utilize iterative schemes or decoupled load flow models. The distribution factors have been popularly used for real power or line security problem, which is computationally much faster than other models. However, no such factors are available for the voltage security problem except the one recently suggested by Lee et al. [29]. The factors suggested are based on fast decoupled load flow approximattions and thus provide quite inaccurate

results. Moreover the factors have been suggested to compute only voltages in case of line contingencies.

Further, almost all works on the ranking methods employ the second order performance indices which suffer from the 'misranking' and 'masking effects'. Masking effect is referred to declaring a contingency case, having few operating constraints violating their limits by large amount, less severe to the cases having more number of operating constrainsts violating by much less amount or having insignificant violation. Misranking of contingencies are mainly due to the inaccuracies in the model used for predicting the post outage state (voltages) of the system.

Hence, the motivations behind the works carried out in this thesis are :

i) To develop a new set of distribution factors to directly compute post outage voltages and reactive power outputs of sources following a line or generator outage. The factors are derived from the network sensitivity properties of Newton-Raphson method Jacobian found at the end of a base load flow results.

ii) To explore new higher order voltage and reactive power performance indices which would eliminate the masking effect and a new method for optimal adjustment of weights used in the performance indices to eliminate the misranking problem.

The effectiveness of the proposed distribution factors and performance indices for voltage contingency selection have been demonstrated on two sample systems.

1.3 THESIS ORGANISATION

The thesis consists of total four chapters.

The present chapter introduces the power system security and voltage contingency problem, presents a brief state of the art mainly on voltage contingency selection problem and sets the motivation behind the present work.

Chapter 2 presents the development of the new set of distribution factors which can be used for computing the post outage voltages and reactive powers following the outage of a line/transformer or a generator.

In Chapter 3 new high order voltage and reactive power performance indices have been defined keeping in view to reduce the masking efect. A method based on least square error minimization has been developed to compute optimal weights of the performance indices which reduces the misranking effect.

Chapter 4 covers the main conclusions of the thesis and suggestions for future scope of research in the area of voltage security contingency selection and analysis.

CHAPTER - 2

VOLTAGE AND REACTIVE POWER DISTRIBUTION FACTORS

2.1 INTRODUCTION

Security analysis for real time monitoring and control of a power system is still a challenging task to power system engineers. Outage of a transmission unit (line or transformer) or a generator may lead to overloads in other healthy branches and generators and/or cause sudden change in the system bus voltages. Operating personnels must know which of the outages will cause flows or voltages to fall outside limits in order to plan for preventive actions. Therefore, fast and accurate methods are necessary to predict the post outage effects in the system. For analysing real power security several fast methods have been suggested in the literature. Amongst them the one based on decoupled load flows [4] or linearized load flow such as [3] and distribution factor derived from D.C. load flow equations [1] are popularly used. The distribution factor methods and D.C. load flows have been widely used in real-time operation and system planning studies to identify branch overloads mainly because of the post outage state of the system can be calculated extremely fast and the approach is simple and direct. In many cases only real power flows may not be adequate in assessing power system security and contingency analysis, in addition, voltage magnitude also becomes a critical factor. Of late the problems associated

with reactive power flows and bus voltages have acquired greater importance. The transmission capacity may sometimes be limited by reactive power considerations. In a few instances voltage collapse in a transmission network has been attributed to abnormal reactive power flow patterns.

For voltage and reactive power contingency analysis, various methods based on A.C. load flow have been reported in literature. Full A.C. load flow methods such as Newton-Raphson load flow (NRLF) or Fast Decoupled Load Flow (FDLF) can not be used for real time applications because of the large computational time. Some of the approximate and fast methods include the linearized load flows, using only one iteration of NRLF or FDLF. These methods, in general provide quite inaccurate results. Some of the attempts to derive the distribution factors for the reactive power or voltage contingency analysis include the efforts of Illic Spong and Phadke [20] and Taylor et al. [28]. Their models are based on decoupled Q-V equations which computes post outage voltages and reactive power using an iterative scheme. They, however, did not suggest a set of factors which can be used for direct calculation of post outage state. Moreover the inaccuracies in predicting the voltage is as high as 10-30%. Thus, there seems to be no proper attempt to derive set of distribution factors for reactive power and voltage contingency except a recent attempt by Lee and Chen [29]. They suggested only voltage distribution factors for line outages derived from FDLF equations. Since FDLF model itself

ivolves several approximations, the factors suggested are bound to provide quite inaccurate results.

Hence, in this chapter a new set of distribution factors which can be used for direct computation of bus voltages as well as reactive power outputs of sources following a line/transformer or generator outage have been suggested. The voltage and reactive power distribution factors have been derived using base load flow results and an efficient method exploiting the sensitivity properties of NRLF Jacobian available at the end of base load flow. The accuracy of post outage results using the proposed distribution factors have been established on IEEE-14 bus and a practical Indian system.

2.2 REACTIVE POWER FLOW MODEL OF TRANSMISSION UNITS

Two main components of transmission units are transmission line and transformer with on line tap changing (OLTC) provision. Outage of any of these units causes redistribution of reactive power flow in the network and hence the changes in the voltage profile. In order to arrive at a direct method for calculation of new voltage profile and reactive power output of sources, the effect of change in reactive power flow of transmission unit considered for outage from its previous value to zero is required to be studied. Since the reactive power flow in these units at receiving and sending end are different, neither of them can be used to define the outage distribution factors. Hence the average

or transmitted powers have been referred for this purpose as defined below.

Consider π-equivalent model of a transmission line-l connected between bus i and j as shown in Fig. 2.1(a). The complex power from bus i to j ($\overline{S}_{ij} = P_{ij} + j\, Q_{ij}$) can be expressed as,

$$\overline{S}^{*}_{ij} = P_{ij} - j\,Q_{ij} = \overline{V}^{*}_{i}\left[\left(\overline{V}_{i} - \overline{V}_{j}\right)\overline{Y}_{ij} + \overline{V}_{i}\left(J\,B_{cap}\right)\right]$$

where $\overline{Y}_{ij} = (G_{ij} - j\,B_{ij})$ is the series admittance and $J\,B_{cap}$ is the half line charging admittance of the line. Equating the imaginary parts in the above equation, the expression for reactive power flow Q_{ij} can be written as,

$$Q_{ij} = -\left(B_{ij} + B_{cap}\right)V_{i}^{2} - V_{i}V_{j}\,G_{ij}\,\sin\left(\theta_{i}-\theta_{j}\right) + V_{i}V_{j}\,B_{ij}\,\cos\left(\theta_{i}-\theta_{j}\right) \tag{2.1}$$

Similarly, the reactive power flow from bus-j to bus-i can be expressed as,

$$Q_{ji} = -\left(B_{ij} + B_{cap}\right)V_{j}^{2} - V_{i}V_{j}\,G_{ij}\,\sin\left(\theta_{j}-\theta_{i}\right) + V_{i}V_{j}\,B_{ij}\,\cos\left(\theta_{j}-\theta_{i}\right)$$

or

$$Q_{ji} = -\left(B_{ij} + B_{cap}\right)V_{j}^{2} + V_{i}V_{j}\,G_{ij}\,\sin\left(\theta_{i}-\theta_{j}\right) + V_{i}V_{j}\,B_{ij}\,\cos\left(\theta_{i}-\theta_{j}\right) \tag{2.2}$$

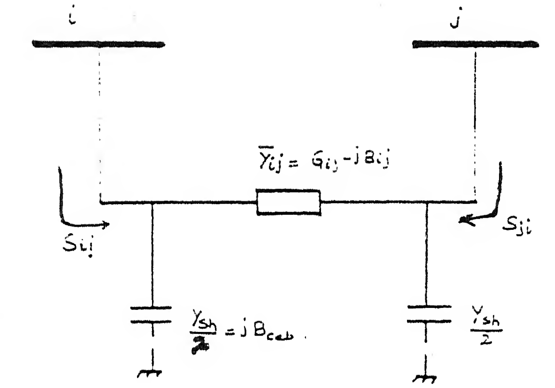

Fig. 2.1a Transmission line π-equivalent model.

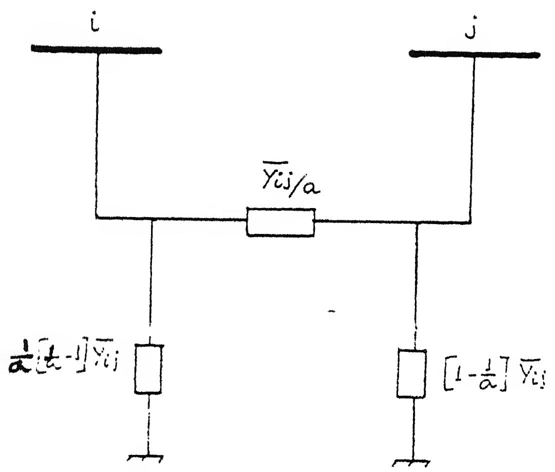

Fig. 2.1b OLTC Transmission π-equivalent model.

The average transmitting reactive power flow in the above line - l, can be defined as

$$Q_l^T = \frac{1}{2}\left[Q_{ij} - Q_{ji}\right]$$

From Eqns. (2.1) and (2.2)

$$Q_l^T = \frac{1}{2}\left[B_{ij} + B_{cap}\right]\left[V_j^2 - V_i^2\right] - V_i V_j\, G_{ij} \sin\left[\theta_i - \theta_j\right] \qquad (2.3)$$

Fig. 2.1(b) shows the π-equivalent model of a transformer with OLTC provisions; 'a' is the tap setting value and $\overline{Y}_{ij}$ is the series admittance of the transformer. Taps are assumed to be provided between transformer and bus-i. The average transmitting reactive power in the transformer having equivalent π-model as shown in Fig. 2.1(b) can also be derived similar to the transmission line.

2.3 PROPOSED DISTRIBUTION FACTORS

In the voltage security or reactive power security studies, the effect of line/transformer or generator outages on the system voltage profile and reactive power output of sources are required to be studied. The outages can be either of a single unit at a time or multiple units simultaneously. However, in the present study, only single unit (line or transformer or generator) outage, which is the most common, have been considered. Since the modelling of transformers are similar to the line, their outages also have been referred to as line outages. The set of proposed

distribution factors for line and generator outages are defined as follows.

Consider the outage of a line/transformer - l carrying the average or transmitted reactive power Q_l^T. The factor to compute change in voltage magnitude (say ΔV_i at a bus-i) has been termed as Line Outage Voltage Distribution Factor (LOVDF) a_{li} and is defined as

$$a_{li} = \frac{\Delta V_i}{Q_l^T} \qquad i = 1,\ldots N \text{ and } l = 1,\ldots,N_L \tag{2.4}$$

For the outage of above line-l for computing the change in the reactive power output of source-j (ΔQG_j) is another set of distribution factors termed as Line Outage Reactive Power Distribution Factors (LOQDFs) C_{lj} are delned as

$$C_{lj} = \frac{\Delta QG_j}{Q_l^T} \qquad j = 1,\ldots,N_Q \text{ and } l = 1,\ldots,N_L \tag{2.5}$$

where N, N_L and N_Q are number of buses, lines and reactive power sources (including generators, & synchronous condensers) in the system.

Now instead of line outage, consider the outage of a generator - g carrying a power QG_g during pre-outage condition. Due to this outage assume that the change in voltage at bus-i is ΔV_i and the reactive power of source-j is ΔQG_j ($j \neq g$). These changes in voltage and reactive powers can be computed with the help of distribution factors termed as Generator Outage Voltage

Distribution Factor (GOVDF) 'b_{gi}' and Generator Outage Reactive Power Distribution Factor (GOQDF) d_{gj} respectively, defined as follows

$$b_{gi} = \frac{\Delta V_i}{QG_g} \qquad \begin{array}{l} i = 1,..,N \\ g = 1,..,N_Q \end{array} \tag{2.6}$$

and

$$d_{gj} = \frac{\Delta QG_j}{QG_g} \qquad \begin{array}{l} j = 1,..,N_Q \\ \quad \neq g \\ g = 1,..,N_Q \end{array} \tag{2.7}$$

The above four sets of distribution factors can be computed directly from base case load flow results utilizing sensitivity properties of Jacobian matrix as described in the subsequent section. These factors can be directly used to compute the post contingency system voltage profile and reactive power outputs of sources. If the post contingency voltage at bus-i is V_i^n and the reactive power output of source-j is QG_j^n following outage of line-l or generator-g, and their base values are V_i^o and QG_j^o respectively, then the post outage values using the distribution factors can be computed as,

<u>For line-l outage</u>

$$V_i^n = V_i^o + a_{li} \cdot Q_l^T \qquad i = 1,..,N \tag{2.8}$$

$$QG_j^n = QG_j^o + c_{lj} \cdot Q_l^T \qquad j = 1,..,N_Q \tag{2.9}$$

For Gen-g outage

$$V_i^n = V_i^o + b_{gi} \cdot QG_g \qquad i = 1,\ldots,N \tag{2.10}$$

$$QG_j^n = QG_j^o + d_{gj} \cdot QG_g \qquad j = 1,\ldots,N_Q \; \neq g \tag{2.11}$$

2.4 A SENSITIVITY BASED APPROACH TO COMPUTE DISTRIBUTION FACTORS

For computing voltage and reactive power distribution factors as defined in Eqns. (2.4) to (2.7), the base case line flows, output of sources and the effect of each outage on bus voltage and reactive power outputs of sources are required to be known. A new approach to compute the post outage changes in bus voltage magnitudes and reactive power generations, utilizing the sensitivity properties of the Newton-Raphson base case load flow Jacobian, has been suggested. The N.R.L.F. equations in polar coordinates [2] relate power mismatch with voltage corrections as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \tag{2.12}$$

When Q-limits of the sources are considered the size of Jacobian [J] will be $(2N-N_Q + m -1) \times (2N - N_Q + m - 1)$, where m is the number of P-V buses converted to P-Q type following the violation of generator Q-limits. Consider an extended Jacobian $[J^*]$ of size $(2N-2)\times(2N-2)$ considering all source buses (except slack) as P-Q type. The $[J^*]$ can be formed at the end of load flow easily by augmenting $\partial Q/\partial\delta$ and $(\partial Q/\partial V.V)$ elements

corresponding to all P-V buses in the final Jacobian [J]. A sensitivity matrix [S] can be defined as $[S] = [J^*]^{-1}$, which is formed at the end of base load flow directly provides sensitivity relations between bus powers and voltages and can be used to compute new bus voltage angles and magnitudes, if the changes in bus power injections are known. The relationship can be written as

$$\begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = \begin{bmatrix} S \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (2.13)$$

If the generator or line outages are simulated as changes in bus real and reactive power injections, the post outage changes in voltage magnitude and angles can be computed using Eqn. (2.13). With the known new complex bus voltages, the new reactive power outputs of sources and hence the changes in the outputs can be computed. The attractive feature of this approach is that it does not require any additional load flow iterative simulation of contingencies and hence distribution factors and post outage conditions can be calculated very fast. The procedure for simulating line and generator outages in the sensitivity relationship and clauclation of the distribution factors is given below.

2.4.1 Line Outage Voltage Distribution Factors

Fig. 2.2(a) shows the pre-outage state of a part of a power system network, where line-l conencting bus i and j is to be considered for outage study.

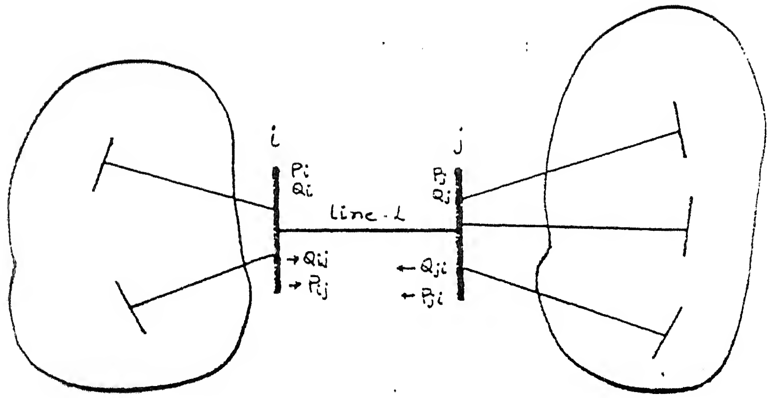

Fig. 2.2a Pre-outage (original) state of power system.

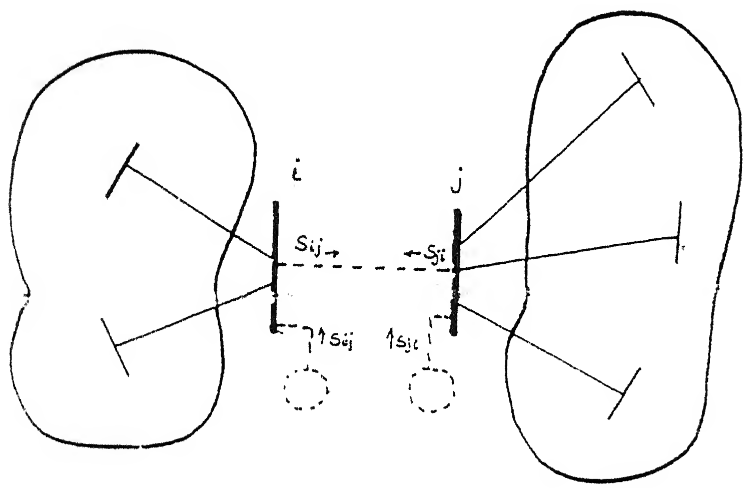

Fig. 2.2b Post-outage (final) state of power system.

Fig. 2.2(b) shows the post outage state of power system in which line-l is out of service. Usual simulation of the line outage requires modification of 'Y_{bus}' to exclude the parameters of line-l which changes the Jacobinan and hence will involve a time extensive process. In order to retain the original 'Y_{bus}', elements of Jacobinan and sensitivity matrix, line outage has been simulated by considering two fictitious generators at bus-i and bus-j, the two terminal ends of the line. If the power output of the two fictitious sources are same as the line flows at the two ends, the net power will be zero thus simulating the outage condition.

Thus, changes in bus powers from pre-outage to post-outage state at buses i and j for outage of line-l are,

$$\Delta P_i = P_{ij}, \quad \Delta Q_i = Q_{ij}$$

$$\Delta P_j = P_{ji} \text{ and } \Delta Q_j = Q_{ji} \tag{2.14}$$

For the outage of the line-l these four elements are entered in the right hand side vector of Eqn. (2.13) and all other remaining elements in this vector will be zero. If either bus-i or j is the slack bus, only two non-zero elements will appear in the [ΔP, ΔQ] vector.

The solution of Eqn. (2.13) gives the changes in bus voltage angles and magnitudes from pre-outage to post-outage condition. With the changes in voltage magnitude at all the buses known (slack bus voltage assumed to be constant), the line outage

voltage distribution factors can be computed using Eqn. (2.4) where Q_l^T is computed from base load flow results using Eqn. (2.3). The factors can be calculated for each line outage, considering one at a time for ($l = 1,2,..,N_L$), on similar approach. Thus the total number of LOVDF's will be $N_B x N_L$ which can be stored in computer memory, say as matrix [A], to carry out voltage contingency analysis.

2.4.2 Generator Outage Voltage Distribution Factors

Fig. 2.3(a) shows the part of a power system, where generator g, which is connected to bus i, is under consideration for outage study. Fig. 2.3(b) shows the post outage state of power system in which generator g is out of service. In this state

$$P_i' = P_i - P_g$$

$$\text{and} \quad Q_i' = Q_i - Q_g \tag{2.15}$$

where P_i' and Q_i' are respectively the real and reactive power of bus-i in post outage state.

Thus changes in ith bus power from pre-outage to post-outage are given by

$$\Delta P_i = - P_g \quad \text{and} \quad \Delta Q_i = - Q_g \tag{2.16}$$

All other elements of ΔP and ΔQ vector will be zero. With these ΔP and ΔQ, the Eqn. (2.13) is solved to compute changes in bus voltage magnitudes (ΔV). The GOVDFs can be computed for outage of

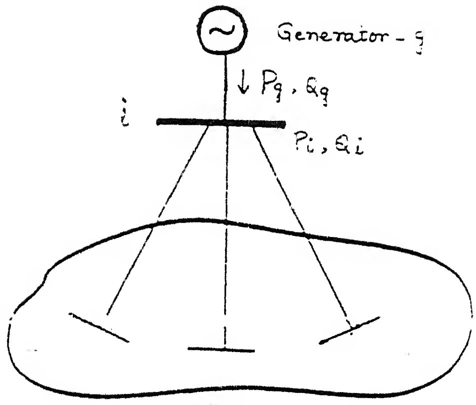

Fig 2.3a Pre-outage (original) state of power system.

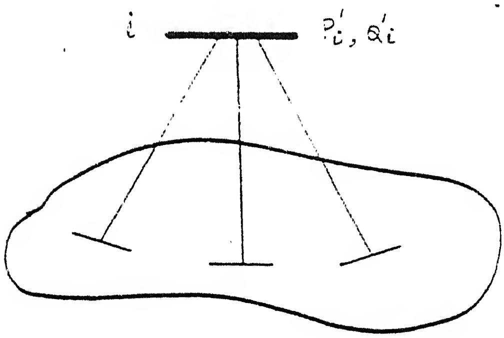

Fig. 2.3b Post-outage (final) state of power system.

each generator taken one at a time using Eqn. (2.6). The GOVDFs thus obtained, are stored in the computer memory, say as matrix B for conducting contingency analysis. Outage of slack bus generator can not be simulated in Eqn. (2.13) as it excludes elements corresponding to the slack bus. However, its simulation will require considering another generator bus as slack and redefining matrix [S] accordingly. In the present study, outage of the slack generator has not been considered.

2.4.3 Line Outage Reactive Power Distribution Factors

In certain voltage security studies, the effect of outages on outputs of reactive power sources, instead of bus voltages are required to be computed. The calculation of such factors requires the base load flow to be run without considering the Q-limits of sources. Thus the sensitivity relationship is redefined as,

$$\begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = \begin{bmatrix} S' \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{2.17}$$

where [S'] is the inverse of load flow Jacobian directly available at the end of base load flow and has dimension $(2N-N_Q-1)x(2N-N_Q-1)$. Consider the outage of a line-l. The change in bus voltages are calculated exactly in the similar lines as in section 2.3 for voltage distribution factors but using Eqn. (2.17) instead of (2.13). The LOQDFs can be computed using Eqn. (2.5) for each line outages simulated one at a time. In this case if either bus-i or j is P-V type bus then the corresponding ΔQ

element will not appear on RHS vector in Eqn. (2.17) thus reducing the non-zero elements to 3.

Using the computed new voltages and the bus reactive powers at Q-sources and hence their reactive power output and the change in reactive power outputs from pre-outage to post-outage can be computed. LOQDFs can be calculated using Eqn. (2.5) for each line outage taken one at a time.

Thus, the total number of LOQDFs is $N_L x N_Q$ which are stored in the memory of computer, say as matrix [C] for contingency analysis.

2.4.4 Generator Outage Reactive Power Distribution Factors

Consider the outage of a generator-g. The change in bus voltages magnitude and angles are computed exactly on the same lines in section 2.4.2 but using Eqn. (2.17). The post-outage voltages are thus computed by adding the changes in voltages to the base case voltages. Using the post-outage voltages, the bus reactive powers at all other source buses and hence the reactive outputs of the Q-sources and the change in reactive power generation from pre-outage to post-outage are computed. The GOQDFs can be calculated for outage of all the generators taken one at a time using Eqn. (2.7). These GOQDFs are stored in the memory of the computer, say as matrix [D] for contingency analysis.

2.5 SYSTEM STUDIES AND RESULTS

To establish the effectiveness of the proposed distribution factors, studies were carried out on two sample systems : (i) IEEE-14 bus system as described in Appendix-A and (ii) a practical 19-bus Indian system representing 400 kV, UP State Electricity network described in Appendix-B. The IEEE-14 bus system contains 20 lines, three generators and two synchronous condensers whereas the Indian system contains 24 lines and 4 generators. For the present study, contingencies of all the lines taken one at a time for both the systems and outage of only two generators (gen-2 & 3) in 14 bus and outge of three generators (gen-2, 3 & 4) in 19 bus Indian system, taken one at a time, were simulated.

The computer simulation of both the systems were carried out on HP 9000 computer. The distribution factors were computed for base case loadings as mentioned in Appendices A and B. The line generator outage voltage and reactive power distribution factors for IEEE-14 bus system are given in Table 2.1. To establish the accuracy of the distribution factors method, for obtaining post-outage bus voltage magnitudes and the reactive power outputs, the results have been compared with those obtained using full AC load flow method employing NRLF in polar coordinates. The comparison for some of the contingency cases are presented in Tables 2.2 and 2.3. It can be observed that the bus voltages obtained using the proposed distribution scheme are very close to that of full AC load flow with a error of around 3%. However, the error in predicting the reactive power output is more. The full

AC load flow did not converge for line-1 outage, whereas the results of post-outage voltages were obtained through distribution factors.

The voltage and reactive power distribution factors computed for the 19 bus Indian system are shown in Table 2.4. The comparison of post-outage bus voltages and reactive powers using full AC load flow and distribution factors technique for few contingency cases are shown in Tables 2.5 & 2.6. It is interesting to note that out of the 27 contingencies simulated, the full AC load flow method converged only for 15 cases and did not converge for remaining 12 cases. However, the post outage state can be predicted using the distribution factors method. The comparison of voltages (Table 2.5) shows that the voltages obtained from distribution factor methods are quite close to that obtained by exact load flow. The error is around 5%. The error in predicting the reactive power is however significant.

Further, it was felt worth exploring the accuracy of predicting post outage states for changes in system loading. To study this effect, the loading of 14 bus system was increased by 5% and 10% and was decreased by the same 5% and 10% from their base values. The real and reactive power loadings were changed at all the buses simultaneously to simulate the above condition. The comparison of voltage predicted using the distribution factors and the full AC load flow method for a sample contingency (outage of line-11) are presented in Table 2.7. It can be observed from this table (Table 2.7) that for decrease in loading even upto 10%, the

predicted voltage values are quite accurate. However, for increased loading condition the results are accurate only upto 5% increase. Thus, the distribution factors need not be recomputed for slight change in loading in this range.

2.6 CONCLUSIONS

In this chapter new set of voltage and reactive power distribution factors for both line and generator outages have been suggested. The voltage contingency studies conducted on two sample systems reveal that,

i) The prediction of post outage bus voltages using the distribution factors are quite accurate and provides the results with a error of 3% in IEEE-14 bus system and 5% in the Indian system. However, with the use of distribution factors, the error in predicting the reactive power output of sources is higher.

ii) Since the distribution factors are obtained directly from base load flow results without involving any iterative scheme or the additional load flow solution, its calculation and updating is quite fast and can be carried out on real time basis.

iii) The set of distribution factors computed at a base loading accurately predicts the post outage voltages of the system even for small change in system loading. Thus, they need not be recomputed for small deviation in system loading (about ± 5%). This further reduces the computational time for the voltage contingency analysis.

TABLE-2.1a

LINE OUTAGE VOLTAGE DISTRIBUTION FACTORS (LOVDFs)

Line No	Bus No. 1	2	3	4	5	6	7
1	.000	.031	.029	.031	.030	.031	.032
2	.000	.695	1.340	.956	1.255	1.273	1.313
3	.000	.131	.299	.614	.322	.326	.335
4	.000	-.028	-.511	-.222	-.442	-.448	-.466
5	.000	-2.920	-17.959	-11.528	-20.564	-20.852	-21.402
6	.000	-.008	.070	-.018	-.080	-.082	-.108
7	.000	-.005	-.013	-.010	-.024	-.024	-.030
8	.000	-.006	.004	-.012	-.037	-.038	-.048
9	.000	-.018	-.033	-.015	-.036	-.037	-.037
10	.000	.001	.002	.001	-.171	.004	.003
11	.000	-.007	-.041	-.011	.001	.001	-.103
12	.000	.000	-.020	.001	.012	.012	.017
13	.000	-.001	-.072	.000	.028	.028	.041
14	.000	.003	-.134	.002	-.056	-.056	-.091
15	.000	.002	-.050	.006	-.122	-.124	-.081
16	.000	.012	-.060	.023	-.015	-.015	-.059
17	.000	-.032	-.034	-.058	-.085	-.086	-.089
18	.000	.011	-.101	.024	.106	.108	.140
19	.000	-.002	.015	-.004	-.019	-.019	-.025
20	.000	-.017	.102	-.036	-.145	-.147	-.190

Line No.	Bus No. 8	9	10	11	12	13	14
1	.027	.028	.032	.031	.030	.030	.032
2	1.260	1.175	1.327	1.335	1.361	1.361	1.361
3	.256	.308	.331	.313	.297	.303	.328
4	-.499	-.404	-.476	-.494	-.517	-.514	-.496
5	-15.683	-19.745	-21.043	-19.691	-18.472	-18.911	-20.777
6	-.005	-.026	-.169	-.316	.059	.041	-.046
7	-.009	-.013	-.028	-.022	-.488	-.120	-.070
8	-.009	-.016	-.040	-.020	-.093	-.235	-.131
9	-.027	-.036	-.036	-.035	-.034	-.034	-.036
10	.001	.002	.003	.003	.002	.002	.003
11	-.018	-.013	-.094	-.070	-.045	-.053	-.083
12	-.001	.002	-.070	-.046	-.017	-.015	.003
13	-.010	.001	.023	-.022	-.102	-.138	-.338
14	.009	.002	-.103	-.122	-.132	-.134	-.113
15	.003	.008	-.074	-.061	-.054	-.054	-.070
16	.025	.031	-.055	-.052	-.064	-.056	-.057
17	-.020	-.023	-.082	-.061	-.037	-.044	-.073
18	.002	.035	.227	-.333	-.088	-.060	.057
19	-.002	-.006	-.019	-.003	.374	-.147	-.080
20	-.013	-.052	-.148	-.035	.171	.281	-.633

TABLE-2.1b

GENERATOR OUTAGE VOLTAGE DISTRIBUTION FACTORS (GOVDFs)

Gen. No.	Bus No 1	2	3	4	5	6	7
2	.000	-.069	-.061	-.066	-.064	-.064	-.066
3	.000	-.075	-.362	-.121	-.211	-.214	-.241

Gen. No.	Bus No 8	9	10	11	12	13	14
2	-.055	-.061	-.066	-.064	-.063	-.063	-.065
3	-.156	-.157	-.263	-.311	-.359	-.350	-.294

TABLE 2.1c

LINE OUTAGE REACTIVE POWER DISTRIBUTION FACTORS (LOQDFs)

Line No.	Q - Source No. 1	2	3	4	5
1	.3770	-1.1835	-.0001	-.0006	.0000
2	-3.1415	-.2444	.0004	-.0190	.0004
3	-.9942	.6615	-.0006	-1.3051	.0001
4	2.7673	.9050	-.0004	.0206	-.0002
5	-8.7872	.0086	-.0131	-.1601	.0011
6	.1901	.0000	1.0926	.0000	.0000
7	.1257	.0000	1.0603	.0000	.0000
8	.1395	.0000	1.0693	.0000	.0000
9	.2307	.0064	.0000	.9960	.0000
10	-.0104	.0000	.0000	.0000	-1.0135
11	.1817	.0000	.0020	.0000	.0000
12	.0017	.0000	.0000	.0000	.0000
13	.0551	.0000	.0012	.0000	.0000
14	-.1177	-.0002	-1.1995	.0000	.0000
15	-.0905	.0000	-.0018	.0000	.0001
16	-.5397	-.0001	-.0095	.0000	.0000
17	.2702	.0069	.0016	.0016	.0000
18	-.8045	-.0002	-.0307	.0000	.0000
19	.0434	.0000	.0025	.0000	.0000
20	.5172	.0001	.0145	.0000	.0000

TABLE 2.1d

GENERATOR OUTAGE REACTIVE POWER DISTRIBUTION FACTORS (GOQDFs)

Gen. No.	Q - Source No. 1	2	3	4	5
2	1.1904	.0000	.0004	-.0022	-.0001
3	1.8875	.0108	.0000	-.0009	-.0004

TABLE-2.2

COMPARISON OF POST-OUTAGE VOLTAGES OBTAINED USING FULL AC LOAD FLOW AND DISTRIBUTION FACTORS METHOD

Bus No.	Line-10		Gen- 2		Line-15 (Transformer-2)	
	ACLF	Factors	ACLF	Factors	ACLF	Factors
1	1.000	1.000	1.000	1.000	1.000	1.000
2	0.990	0.992	0.961	0.958	0.991	0.992
3	1.000	1.000	0.991	1.000	1.000	1.006
4	0.965	0.969	0.943	0.969	0.967	0.968
5	1.000	1.014	1.000	1.000	1.000	1.014
6	0.972	0.986	0.975	0.986	0.983	1.000
7	0.970	0.979	0.967	0.980	0.972	0.989
8	0.964	0.967	0.949	0.967	0.965	0.967
9	0.958	0.962	0.942	0.962	0.960	0.961
10	0.967	0.975	0.963	0.975	0.968	0.983
11	0.979	0.983	0.973	0.983	0.979	0.990
12	0.983	0.984	0.974	0.984	0.983	0.990
13	0.976	0.978	0.968	0.978	0.976	0.984
14	0.953	0.959	0.948	0.959	0.954	0.967

TABLE-2.3

COMPARISON OF POST-OUTAGE Q-SOURCE REACTIVE POWER OUTPUTS OBTAINED BY FULL AC LOAD FLOW AND DISTRIBUTION FACTORS METHOD

Q-Source	Line-10		Gen.-2		Line-15 (Transformer-2)	
No.	ACLF	Factors	ACLF	Factors	ACLF	Factors
1	-0.4480	-0.4524	-0.0994	0.1539	-0.4473	-0.4449
2	0.5267	0.5098	0.0000	0.0000	0.5140	0.5092
3	0.1673	0.1440	0.1980	0.1442	0.1462	0.1441
4	0.6491	0.6382	0.8231	0.6371	0.6378	0.6382
5	0.0192	0.1017	0.0771	0.0520	0.0873	0.0521

TABLE-2.4a

LINE OUTAGE VOLTAGE DISTRIBUTION FACTORS (LOVDFs)

	⟨--------------			Bus No.		--------------⟩
Line No.	1	2	3	4	5	6	7
1	.000	.055	.065	.059	.063	.051	.065
2	.000	-.045	-.046	-.038	-.044	-.027	-.046
3	.000	-.029	-.036	-.027	-.029	-.023	-.027
4	.000	-.024	-.024	-.035	-.023	-.017	-.024
5	.000	-.004	-.005	-.004	-.004	-.003	-.005
6	.000	-.743	-.738	-.676	-.736	-.561	-.741
7	.000	.626	.629	.569	.619	.472	.631
8	.000	.011	.012	.012	.011	.010	.012
9	.000	.026	.026	.023	.026	.018	.026
10	.000	.209	.212	.183	.207	.149	.213
11	.000	.135	.138	.119	.134	.096	.138
12	.000	.365	.371	.323	.362	.265	.372
13	.000	-.286	-.289	-.258	-.283	-.213	-.290
14	.000	-12.089	-12.244	-10.813	-11.963	-8.879	-12.291
15	.000	-.230	-.232	-.208	-.228	-.171	-.233
16	.000	.142	.143	.128	.141	.105	.144
17	.000	.269	.271	.242	.266	.199	.272
18	.000	.294	.296	.264	.291	.217	.297
19	.000	-.512	-.517	-.460	-.507	-.378	-.519
20	.000	-.595	-.588	-.528	-.579	-.429	-.590
21	.000	-.019	-.019	-.017	-.018	-.013	-.019
22	.000	-.153	-.153	-.138	-.151	-.114	-.154
23	.000	-1.316	-1.320	-1.194	-1.303	-.985	-1.325
24	.000	-.252	-.254	-.227	-.250	-.187	-.255

	⟨--------------			Bus No.		--------------⟩
Line No	8	9	10	11	12	13	14
1	.060	.082	.089	.112	.163	.168	.165
2	-.038	-.052	-.055	-.072	-.105	-.108	-.107
3	-.027	-.037	-.040	-.050	-.073	-.075	-.074
4	-.020	-.028	-.031	-.040	-.058	-.060	-.059
5	-.004	-.005	-.005	-.007	-.010	-.010	-.010
6	-.680	-.880	-.936	-1.142	-1.587	-1.628	-1.601
7	.572	.740	.787	.961	1.340	1.376	1.354
8	.012	.017	.018	.021	.031	.031	.031
9	.023	.030	.035	.043	.062	.064	.063
10	.184	.140	.202	.287	.443	.456	.451
11	.120	.096	.113	.172	.274	.283	.280
12	.325	.321	.324	.478	.746	.769	.759
13	-.259	-.294	-.285	-.317	-.524	-.541	-.536
14	-10.869	-12.243	-12.536	-14.842	-23.670	-24.417	-24.147
15	-.209	-.246	-.249	-.267	-.347	-.361	-.360
16	.129	.150	.152	.166	.155	.166	.174
17	.243	.285	.290	.321	.320	.301	.303
18	.265	.309	.313	.343	.326	.345	.352
19	-.463	-.539	-.551	-.627	-.763	-.777	-.757
20	-.531	-.678	-.717	-.879	-1.223	-1.256	-1.237
21	-.017	-.020	-.021	-.025	-.033	-.034	-.033
22	-.139	-.178	-.189	-.228	-.301	-.307	-.300
23	-1.200	-1.539	-1.628	-1.966	-2.597	-2.647	-2.583
24	-.228	-.269	-.274	-.305	-.308	-.303	-.283

contd ...

Line No.	15	16	17	18	19
1	.114	.114	.143	.145	.165
2	-.075	-.075	-.094	-.095	-.107
3	-.051	-.050	-.063	-.064	-.074
4	-.041	-.041	-.051	-.052	-.059
5	-.007	-.007	-.009	-.009	-.010
6	-1.043	-1.034	-1.297	-1.315	-1.600
7	.886	.879	1.102	1.118	1.353
8	.021	.021	.026	.027	.031
9	.044	.043	.054	.055	.063
10	.334	.333	.418	.424	.450
11	.214	.213	.268	.271	.280
12	.571	.570	.714	.724	.759
13	-.426	-.426	-.534	-.542	-.535
14	-18.569	-18.535	-23.237	-23.564	-24.130
15	-.318	-.318	-.399	-.404	-.360
16	.195	.195	.245	.248	.174
17	.364	.366	.458	.465	.303
18	.402	.404	.506	.513	.352
19	-.688	-.692	-.867	-.879	-.757
20	-.807	-.806	-1.010	-1.024	-1.236
21	-.020	-.024	-.030	-.031	-.033
22	-.182	-.180	-.177	-.179	-.300
23	-1.568	-1.547	-.553	-.482	-2.581
24	-.340	-.342	-.428	-.434	-.305

TABLE-2.4b

GENERATOR OUTAGE VOLTAGE DISTRIBUTION FACTORS (GOVDFs)

	<-------------		Bus No.	------------->	
Gen. No.	1	2	3	4	5
2	.000E+00	-.146E+07	-.170E+07	-.160E+07	-.166E+07
3	.000E+00	.148E-01	.788E-02	.133E-01	.147E-01
4	.000E+00	.123E-01	.126E-01	-.630E-03	.122E-01

	<-------------		Bus No.	------------->	
Gen. No.	6	7	8	9	10
2	-.150E+07	-.171E+07	-.161E+07	-.229E+07	-.257E+07
3	.101E-01	.141E-01	.134E-01	.175E-01	.180E-01
4	.781E-02	.126E-01	.102E-01	.144E-01	.149E-01

	<-------------		Bus No.	------------->	
Gen. No.	11	12	13	14	15
2	-.305E+07	-.439E+07	-.451E+07	-.443E+07	-.304E+07
3	.244E-01	.361E-01	.373E-01	.369E-01	.260E-01
4	.200E-01	.295E-01	.303E-01	.299E-01	.210E-01

	<--------	Bus No.	-------->	
Gen. No.	16	17	18	19
2	-.300E+07	-.377E+07	-.382E+07	-.443E+07
3	.260E-01	.326E-01	.331E-01	.369E-01
4	.210E-01	.263E-01	.267E-01	.299E-01

TABLE 2.4c

LINE OUTAGE REACTIVE POWER DISTRIBUTION FACTORS
(LOQDFs)

Line No	1	2	3	4
	(---------	Q - Source No.	---------)	
1	9.8272	-5.5705	.0005	.0008
2	2.7157	.0002	.0004	.0003
3	11.2277	.0002	-6.0433	.0008
4	6.0715	.0002	.0003	-4.1999
5	1.1437	.0000	.0000	.0000
6	32.3986	-.0589	-.0285	-.0070
7	-30.1851	.2818	.1720	.0634
8	.1053	.0000	.0000	.0000
9	2.5954	.0001	.0001	.0001
10	-16.2504	.0043	.0006	-.0013
11	-6.8581	-.0001	-.0005	-.0005
12	-46.8585	.0213	.0063	-.0028
13	10.7590	-.0015	.0002	.0009
14	-154.6911	.3120	.1648	.0367
15	11.7321	-.0262	-.0138	-.0034
16	-8.2976	.0016	.0000	-.0007
17	-15.9117	.0047	.0008	-.0012
18	-16.6533	.0013	-.0008	-.0015
19	24.6918	-.0831	-.0467	-.0135
20	22.8610	-.0336	-.0162	-.0029
21	1.4885	.0000	.0000	.0000
22	8.4967	-.0093	-.0041	-.0005
23	56.1069	-.0386	-.0144	.0010
24	14.2014	.0004	.0006	.0005

TABLE 2.4d

GENERATOR OUTAGE REACTIVE POWER DISTRIBUTION FACTORS
(GOQDFs)

Gen No.	1	2	3	4
	(--------	Q - Source No.	--------)	
2	.3419E+01	.0000	-.4363E-04	-.3827E-04
3	.2291E+01	-.1098E-04	.0000	-.1199E-04
4	.1613E+01	-.5923E-05	-.6996E-05	.0000

TABLE-2.5

COMPARISON OF POST-OUTAGE VOLTAGES OBTAINED USING FULL AC LOAD FLOW AND DISTRIBUTION FACTORS METHOD

Bus No.	Line-5		Gen.-3	
	ACLF	Factors	ACLF	Factors
1	1.030	1.030	1.030	1.030
2	1.030	1.015	1.030	1.034
3	1.030	1.035	1.072	1.042
4	1.030	1.033	1.030	1.050
5	1.009	1.017	1.015	1.036
6	1.003	1.016	1.007	1.029
7	1.020	1.021	1.012	1.037
8	1.007	1.017	1.013	1.034
9	0.958	0.985	0.976	1.007
10	0.954	0.987	0.975	1.009
11	0.936	0.984	0.973	1.014
12	0.938	1.014	0.998	1.059
13	0.952	1.028	1.012	1.074
14	0.925	1.019	1.003	1.065
15	0.958	1.010	1.000	1.042
16	0.960	1.011	1.001	1.043
17	0.976	1.042	1.029	1.082
18	0.978	1.044	1.032	1.085
19	0.947	1.021	1.005	1.066

TABLE-2.6

COMPARISON OF POST-OUTAGE Q-SOURCE REACTIVE POWER OUTPUTS OBTAINED BY FULL AC LOAD FLOW AND DISTRIBUTION FACTORS METHOD

Q-Source No.	Line-9		Gen.-2	
	ACLF	Factors	ACLF	Factors
1	0.613	0.347	1.254	2.002
2	1.686	1.034	1.281	1.034
3	0.954	0.645	0.744	0.455
4	0.627	0.455	0.000	0.000

TABLE-2.7

COMPARISON OF VOLTAGES PREDICTED BY THE DISTRIBUTION FACTORS METHOD AND THE FULL AC LOAD FLOW METHOD FOR A SAMPLE CONTINGENCY WITH DIFFERENT LOADING CONDITIONS

Bus No	0.9 PU		0.95 PU		1.05 PU		1.10 PU	
	ACLF	Factors	ACLF	Factors	ACLF	Factors	ACLF	Facto
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
2	0.999	0.999	0.992	0.996	0.998	0.998	0.984	0.98
3	1.000	1.000	1.000	1.000	1.000	1.000	0.993	0.99
4	0.982	0.982	0.969	0.976	0.961	0.961	0.952	0.95
5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.00
6	0.992	0.992	0.986	0.989	0.983	0.983	0.977	0.97
7	0.987	0.987	0.979	0.983	0.975	0.975	0.968	0.96
8	0.975	0.975	0.967	0.971	0.963	0.963	0.957	0.95
9	0.971	0.971	0.962	0.967	0.957	0.957	0.950	0.95
10	0.982	0.982	0.975	0.978	0.971	0.971	0.963	0.96
11	0.987	0.987	0.983	0.985	0.981	0.981	0.973	0.97
12	0.989	0.987	0.988	0.986	0.988	0.985	0.980	0.97
13	0.979	0.981	0.976	0.979	0.974	0.975	0.966	0.96
14	0.966	0.967	0.958	0.963	0.954	0.955	0.945	0.94

CHAPTER - 3

PERFORMANCE INDICES FOR VOLTAGE CONTINGENCY SELECTION

3.1 INTRODUCTION

Contingency selection problem is concerned with developing computer algorithms for quickly identifying those contingencies which may cause out-of-limit conditions so as to reduce the number of contingencies that need to be evaluated by full A.C. load flow when assessing the power system's security. Almost all contingency ranking algorithms employ a scalar performance index (PI) which is a function of chosen network variables. For contingency analysis, the PI value represents the degree to which the system operating state is approaching or exceeding its static limits.

In planning studies, the traditional approach for steady state contingency analysis is to test all contingencies sequentially to evaluate system performance and reliability. This analysis consists of simulating outages of one or more generating and transmission units to investigate their effects on bus voltages and line power flows. However, exhaustive contingency testing including all conceivable contingencies, becomes a prohibitively time extensive when all primary contingencies, each with additional levels of secondary contingencies are involved. On the other hand, applying contingency testing to a subset of contingency cases selected only on the basis of the planner's

experience and intuition may be inadequate due to the possibility of omitting some critical cases.

In real time, as the system conditions change, the contingencies which cause insecure operation may also change, and would be different from those predicted by off-line simulation studies. Therefore, the selection of contingencies to be studied by the on-line security analysis program should be based on the current operating conditions, but not a fixed list based upon off-line studies. Threfore, ranking based method for contingency selection is popularly used. The method involves calculation of post outage state of system for each contingency using fast but approximate methods and computing their relative severity and ranking them using some performance index.

For voltage contingency selection, various performance indices with bus voltages or reactive power outputs of sources as the monitored variables, have been suggested. They have invariably utilized the second order performance index, which, in general, suffer from 'masking' and 'misranking' effects. Some of the efforts in reducing these drawbacks include the works of Halpin [16] and Schafer [25] who have suggested the method to compute the threshold value and optimal weights of the second order performance indices. The method suggested in ref. [16] for optimal weight selection involves a optimization technique and is quite involved.

In this chapter various existing performance indices for voltage contingencies have been critically reviewed. A more

efective set of voltage and Reactive power indices have been explored which are of higher orders. A simple and fast approach for optimal selection of weights have been suggested which alongwith the proposed higher order performance indices eliminates misranking and masking effects. The outage studies have been simulated using the distribution factors suggested in Chapter-2 and the effectiveness of the new performance indices have been demonstrated on IEEE-14 bus and 19 bus U.P. State Electricity network.

3.2 EXISTING PERFORMANCE INDICES

Use of performance index for ranking of contingencies according to their relative severities was first suggested in 1979 by Ejebe & Wollenberg [6] for both line and voltage securities. Various modified versions for voltage contingency selection were suggested by Albuyeh et al. [10], Medicherla et al. [11] and Wasley et al. [14]. The nature of performance indices alongwith the choice of weighing factors are summarized in Tables ~~2~~.1 and ~~2~~.2 [16] considering respectively the impacts of bus voltage magnitudes and injected reactive powers.

The general form of the various performance indicies is

$$J = \sum_{i} w_i \left[f_i(\underline{Z})^P \right] \tag{3.1}$$

where $f_i(\underline{Z})$ is a linear function of Z_i which denotes either $\left(\Delta V_i / \Delta V_i^{limit}\right)$ or $\left(\Delta QG_i / \Delta QG_i^{limit}\right)$, the changes in load bus voltage

magnitudes or generator bus injections with respect to their target value or ratings respectively. It can be seen from tables

Table 1 : Summary of PI used for measuring the impact of contntingencies on the bus voltage magnitudes.

	Normalized Variable z_i	$f_i(\underline{z})$	Weighing Factor w_i
Ejebe, Wollenberg [6]	$\frac{\Delta V_i}{\Delta V_i^{lim}}$	z_i	α_i
Albuyeh, Bose, Heath [10]	$\frac{\Delta V_i}{\Delta V_i^{lim}}$	$(1-\lvert z_i\rvert)$	$\frac{\alpha_i \Delta V_i^{lim}}{V_i^m}$, if $z_i < -1$ 0, if $-1 \leq z_i \leq 1$ $\frac{\alpha_i \Delta V_i^{lim}}{V_i^M}$, if $z_i > 1$
Medicherla, Rastogi [11]	$\frac{\Delta V_i}{\Delta V_i^{lim}}$	$(z_i + \beta_i)$	$\frac{2P_i \Delta V_i^{lim}}{V_i^o}$
Wasley, Daneshdoost [14]	$\frac{\Delta V_i}{\Delta V_i^{lim}}$	z_i	0, if $\lvert z_i\rvert \leq 1$ 1, if $\lvert z_i\rvert > 1$

Table 2 : Summary of PI used For Measuring the impact of contingencies on the injected reactive power.

	Normalized Variable z_i	$f_i(\underline{z})$	Weighting Factor w_i
Ejebe, Wollenberg [6]	QG_i/QG_i^{non}	z_i	α_i
Albuyeh, Bose, Heath [10]	$\Delta QG_i/\Delta QG_i^{lim}$	$(1-\lvert z_i\rvert)$	$\dfrac{\alpha_i \Delta V_i^{lim}}{V_i^m}$, if $z < -1$ 0, if $-1 \leq z_i \leq 1$ $\dfrac{\alpha_i \Delta QG_i^{lim}}{V_i^M}$, if $z_i > 1$
Wasley, Daneshdoost [14]	$\Delta QG_i/\Delta QG_i^{lim}$	z_i	0, if $\lvert z_i\rvert \leq 1$ 1, if $\lvert z_i\rvert > 1$

1 and 2 that the major difference between the various PIs is the choice of performance function $f(\underline{z})$ and weighing coefficient w_i. Some of the current works have also concentrated on the automatic contingency selection approach. The basic idea has been to compute the changes in PI (i.e., J) for each contingency using an efficient sensitivity method [24]. The work has concentrated on improving the accuracy of the prediction of J obtained via these first order sensitivity methods.

Another work by K. Nara et al. [17] presented a new concept in formulating a PI for contingency selection concerning voltage security analysis. The performance index is defined as a second order vector norm in the voltage space. Two types of voltage limits-alarm limit and security limit are introduced. Each axis of the voltage space is normalized by the difference between these two limits. Contingency cases in which the performance indices are greater than one are selected as severe cases and can be ranked in order of severity. The performance index which includes the effects of generator Q-limit violations and voltage limit violations is defined as follows :

$$\mathrm{PI} = \left[\sum_i \left[\frac{d_i^u(L)}{g_i(L)} \right]^{2n} + \sum_i \left[\frac{d_i^l(L)}{g_i^l(L)} \right]^{2n} \right]^{1/2n} \qquad (3.2)$$

where $\sum_i$ is the total number of buses in the system.

From the PI, the system condition is in,

a secure state if : PI = 0

an alarm state if : $0 < PI \leq 1$

an insecure state if : $PI > 1$

Though different PI ranking algorithms have been reported in the literature, but the common disadvantage of all these methods is, that computationally feasible evaluations have successfully been derived for an exponent of two only. Second order indices have a very limited ability to detect localized system overloading or voltage violations. As a result, severe localized overload lines or voltage violation cases can be given far less importance than would be judged necessary from an engineering aspect. This problem has been termed as the 'masking effect' in contingency selection. The phenomenon of selecting some of the critical contingencies as non-critical is defined as 'masking'. Another problem, which is mainly due to computation of post outage state of the system using approximate methods during contingency slection is the 'misranking' which means inaccurate assignment of order of severity to various contingencies as should have been using the exact method.

Recently, K.F. Schafer et al. have presented a new method to compensate the masking effect in second order PI algorithms [25]. For the PI distribution extended vector norm formulation is introduced, which additionally allows the quantitative description of the masking effect range. They defined the PI as follows

$$PI_{m/k} = \left[\sum_{i=1}^{N} w_i |X_i|^m \right]^{1/m} \tag{3.3}$$

where X_i is a linear function of the system variables, which denotes e.g. $(P_{ij}/P_{ij,max})$ or $(\Delta V_i/\Delta V_{i,max})$, N the number of regarded components (the number of buses and/or branches), m the exponent of the PI function, and w_i a weighing coefficient. The subscript k should indicate the considered contingency k.

In 1984, T.F. Halpin et al. [16] have presented a method for evaluating the effectiveness of the Automatic Contingency Selection (ACS) algorithms in capturing contingencies which give out-of-limit conditions. The evaluation is given in terms of both capture and flase alarm rates, which are computed apriori together with a stopping criterion. The Authors also proposed a method which enhances the ACS algorithm's effectiveness in terms of maximising the capture rate (CR) and minimizing the false alarm rate (FR). Theory has been given for selecting the set of weights in the scalar performance index for both real power and voltage problems in order to circumvent some of the misranking problems, and more importantly, to select the threshold value of the PI in order to capture all the critical contingencies while minimizing the capture of the non-critical ones. The capture rate and false alarm rate have been formulated using the probabilistic approach. The method is, in general, quite cumbersome and time extensive.

3.3 PROPOSED PERFORMANCE INDICES FOR VOLTAGE CONTINGENCY RANKING

Two sets of performance indices are proposed to measure the relative severities of contingencies in terms of their effect on voltage levels and reactive power output of the sources. The voltage level performance index chosen to quantify system deficiency due to out-of-limit bus voltages is defined as

$$PI_v^k = \sum_{i=1}^{N} \frac{w_{vi}}{n} \left(\frac{V_i - V_i^{sp}}{\Delta V_i^{lim}}\right)^n \tag{3.4}$$

where V_i = voltage magnitude at bus i

V_i^{sp} = specified (rated) voltage magnitude at bus i

ΔV_i^{lim} = voltage deviation limit, above which voltage deviations are unacceptable

n = exponent of penalty function

N = number of buses in the system

w_{vi} = real weighing factor

k = outage case number.

The voltage deviation limit ΔV_i^{lim} represents the threshold above which voltage level deviations are outside their limit. Any contingency case with voltage levels outside this yields a high value of the index PI_V. On the other hand, when all the voltage level deviations from the rated voltage are within ΔV_i^{lim} the voltage performance index PI_V is small. Thus, this index measures the severity of the out-of-limit bus voltages, and for a set of contingencies, this index provides a direct means of comparing the

relative severity of the different outages on the system voltage profile.

It is pertinent to note, that since the bus voltage levels depend mainly on the reactive power flows, and therefore, on the reactive power production of the generators and reactive power sources such as synchronous condensers etc., the performance index PI_V provides a good measure of the severity of abnormal voltages, as long as the generating units remain within their reactive power limits. However, it is possible to encounter a contingency for which some generator reactive powers are driven beyond their operating limits. Therefore, in order to reflect the reactive power capability constraints of the generators in the contingency selection for voltage analysis, we define another performance index PI_Q as follows

$$PI_Q = \sum_{i=1}^{N_Q} \frac{w_{Qi}}{n} \left[\frac{QG_i - QG_i^{target}}{\Delta QG_i^{lim}} \right]^n \tag{3.5}$$

where N_Q = number of reactive power sources

n = exponent of penalty function

QG_i = reactive power output of ith source

$$Q_{Gi}^{target} = \frac{1}{2} \left[QG_{i,max} + QG_{i,min} \right]$$

$$QG_i^{lim} = \frac{1}{2} \left[QG_{i,max} - QG_{i,min} \right]$$

In the above expressions $QG_{i,max}$ and $QG_{i,min}$ are respectively the maximum and minimum limits of QG_i. The reactive power deviation limit ΔQG_i^{lim} represents the span that is allowed for QG_i to move away from the target point in either direction (towards $QG_{i,max}$ or $QG_{i,min}$).

Contingency with the reactive power outputs outside this limit results in a greater value of PI_Q^*. On the other hand, when QGs are within the deviation limit ΔQG_i^{lim} then the PI_Q^* is small. Thus, this index PI_Q measures the severity of Q-limits violation of generating units for a particular contingency.

The exponent 'n' in the definition of the two performance indices PI_V and PI_Q in Eqns. (3.4) and (3.5) have been varied from 2 to 20 to explore its desired value or the order of the performance indices, which minimizes the 'Masking effect'. For this set of study all the weights w_i were assumed to be one. In order to eliminate the misranking effects, the proper selection of w_i is required. A simple and effective scheme is described in the subsequent section.

3.4 PROPOSED SCHEME FOR WEIGHTS ADJUSTMENT

An important aspect in the use of P.I. based ranking methods is the proper selection of weights. The improper selection of weights causes misranking of contingencies which is mainly due to the inaccuracies of approximate load flow or distribution factor models in computing post outage states of the system. Some approximate guidelines for selecting the weights are found in

literature as given in Tables 1 and 2. However, as proper attempt has only been made by Halpin et al. [16] who used an optimisation technique to compute the weights. The method maximizes the 'capture rate' and minimizes 'false alarm rate' both formulated as pobabilistic functions and is quite involved. Hence, a simple approach has been proposed in this section, which is based on 'Least Square Error' principle.

The error is defined as the performance index value computed by the distribution factor (D.F.) method and the exact A.C.load flow method. If for kth contingency the performance indices (either PI_V or PI_Q) from the two methods are ~~respectively~~ $(PI^k)_{D.F.}$ and $(PI^k)_{EX}$ respectively the error is defined as

$$E_k = \left(PI^k\right)_{DF} - \left(PI^k\right)_{EX} \tag{3.6}$$

$k \in$ all contingencies.

The proposed method minimizes a function F defined as the sum of the squre of errors

$$F = \sum_{k=1}^{N_c} (E_k)^2 \tag{3.7}$$

where N_c is the total number of contingencies to be considered.

The optimal values of weights are computed off line at some average base operating points and can be used for subsequent calculation. The performance indices computed at this base operating point for different contingencies using exact load flow

model can be computed considering all weightages as unity or the user decided values, if any. Thus, for the above minimization problem, $(PI^k)_{EX}$ are apriori known and constant. Let us assume it to be equal to b_k ($k = 1,..,N_c$).

The post outage states and hence the value of V, ΔV_{limit}, QG and ΔQG_{limit} in Eqns. (3.4) and (3.5) will be known, when each contingency analysed using the D.F. model at the same operating point. If weighing factors for P.I. calculation using D.F. method is considered as unknown, the performance index for kth contingency can be written as

$$\left[PI^k\right]_{D.F.} = \sum_i A_{ki} \cdot w_i \qquad k = 1, \ldots N_c \tag{3.8}$$

$i = 1, .., N$ for voltage P.I.

and $i = 1, .., N_Q$ for reactive power P.I.

A_{ki} is the coefficient and defined from Eqns. (3.4) and (3.5) for known value of n as

$$A_{ki} = \frac{1}{n} \left[\frac{V_i - V_i^{sp}}{\Delta V_i^{lim}} \right]^n \qquad \text{for voltage P.I.} \tag{3.9}$$

and

$$A_{ki} = \frac{1}{n} \left[\frac{QG_i - QG_i^{target}}{\Delta QG_i^{limit}} \right]^n \qquad \text{for reactive power P.I.} \tag{3.10}$$

Thus the function to be minimized is of the form of

$$F = \sum_{k=1}^{N_c} \left[\sum_{i} A_{ki} \cdot w_i - b_k \right]^2 \qquad (3.11)$$

For applying LSE and minimizing error, it is essential that $k > i$ in the above equation, which is generally the case in a power system network.

In vector notation, the error vector can be defined as

$$\bar{E} = A.\bar{W} - \bar{b} \qquad (3.12)$$

where A is the rectangular matrix containing coefficients A_{ki} and $\bar{W}$ is the weight vector and $\bar{b}$ vector contains elements b_k.

Using LSE approach the optimum values of weights can be computed as

$$\bar{W} = \left[A^T A\right]^{-1} A^T \bar{b} \qquad (3.13)$$

Using above equations, the optimum weights for both voltage performance indices [w_{vi} in Eqn. (3.4)] and reactive power performance indices [w_{Qi} in Eqn. (3.5)] can be computed.

3.5 SYSTEM STUDIES AND RESULTS

Simulation studies were carried out on the 14 bus and 19 bus systems as described in Appencides A and B to test the potential of the proposed performance indices defined in Eqns. (3.4) and (3.5) for contingency selection (contingency ranking). All the contingency cases as considered for the two systems in the Chapter-2 were simulated. Results of the voltage contingency

analysis obtained by the exact method and distribution factors were utilized to compute the voltage performance indices assuming all the weightages to be unity. For computing the reactive power performance indices, the load flow was run without checking Q-limit of generators and distribution factors were computed using these results as explained in Chapter-2. Contingency analysis results were obtained using these sets of distribution factors and also by running exact load flow without considering generator Q-limits.

Different forms of voltage and reactive power performance indices were used considering the values of n = 2, 10 and 20 in Eqns (3.4) and (3.5).

The above three sets of voltage performance indices for IEEE-14 bus system using distribution factor's results are presented in table 3.1(a) and those obtained from the exact load flow results are given in table 3.1(b). The reactive power performance indices using distribution factors and exact load flow results are presented in tables 3.2(a) and 3.2(b) respectively. Since exact load flow considering generator Q-limit did not converge for line-1 outage, the voltage performance index (VPI) is not included in table 3.1. The relative severity index of various contingencies are also included in the above tables. It can be observed from these tables that with second order voltage performance index some of the severe contingency cases have been ranked lower than those in which there is no violation of voltage. For IEEE-14 bus system the operating limit of

voltages was considered as 0.95 to 1.05 p.u. whereas in the Indian system it was taken as 0.9 p.u. to 1.1 p.u. This masking effect gradually reduces with the use of higher order performance indices and gets eliminated when exponent n = 20. However, in case of reactive power performance index (QPI) there is no significant change in ranking by using higher than second order performance indices. Similar observations can also be seen in case of 19 bus Indian system as is evident from tables 3.5(a) & 3.5(b)and 3.6(a) and 3.6(b).

In the above study all the weightages (w_{vi} and w_{Qi}) were considered to be unity in both distribution factors method and exact load flow method. In fact one could have used user specified weightages instead of equal weightages considered in the study. The values of performance indices computed with the distribution factors and the exact load flow even with higher order exponent are quite different and provide different rankings to the contingencies. In order to eliminate this misranking problem, the optimal values of weights to be used along with the distribution factors method were computed using least square error (LSF) method for both VPI and QPI in case of IEEE-14 bus system only. The optimal weights so obtained are given in tables 3.3. The performance index values obtained from exact load flow and used in LSE method were their earlier values obtained with all the weights considered as unity. The new values of voltage and reactive power performance indices for the 14 bus system using distribution factors were computed and are compared with those obtained with

the exact load flow method as given in table 3.4. The new performance indices are quite close to those obtained using exact load flow, thus eliminating the misranking effect.

3.6 CONCLUSIONS

In this chapter the higher order performance indices have been proposed and tested on two sample systems. Optimal weights were obtained using LSE method and were used for contingency ranking. The system study reveals that

(1) The use of higher order exponent in voltage performance index eliminates the masking effect. However, it does not improve the results of reactive power performance index. In voltage performance index an exponent of 20 or more is recommended to overcome the masking effect.

(2) With the optimal weights obtained from LSE method, the performance indices computed by the distribution factors matches with those obtained by the exact load flow method thus minimizing the misranking effect.

TABLE-3.1a

COMPARISON OF VPIs OBTAINED BY FACTORS METHOD
WITH VARIOUS EXPONENTS

Outage Line/Gen	VPI 2	VPI 10	VPI 20	Bus Voltage Status
Line No				
1	2 827672	.226510	.104743	–
2	5 314006(03)	2.778026(03)	14.833389(03)	V
3	4 163833(04)	1.785841(04)	6.835161(04)	V
4	2 715189(06)	.212892(06)	.099986(07)	V
5	3 602287(05)	687767(05)	1.021348(05)	V
6	1 707697(12)	029307(13)	.001947(14)	NV
7	1 677059(13)	028740(14)	.002040(13)	NV
8	2 024801(08)	112868(08)	.045080(08)	NV
9	2 004540(09)	.068496(11)	.010516(11)	NV
10	1 549901(15)	.022591(17)	.001142(17)	NV
11	1 805896(11)	.050743(12)	.007924(12)	NV
12	1 545378(16)	.021238(18)	.000964(18)	NV
13	1 813930(10)	224596(07)	.232471(06)	V
14	999576(21)	009908(21)	.000254(21)	NV
15	1 171060(20)	012174(20)	.000349(20)	NV
16	1 434549(19)	.019421(19)	.000698(19)	NV
17	2 034158(07)	.077613(10)	.013256(10)	NV
18	1 528565(17)	.024652(15)	.001375(15)	NV
19	1 502065(18)	.023330(16)	.001262(16)	NV
20	1 672920(14)	.088927(09)	.031188(09)	NV
Gen No				
2	7 502298(02)	.10141E+0(02)	.15848E+03(02)	V
3	12 412277(01)	.15024E+0(01)	.36853E+05(01)	V

Note V Violating
NV Non-Violating
Number given in pranthesis refers to ranking.
VPI 2 Voltage Performance Index with exponent 2

TABLE 3.1b

COMPARISON OF VPIs OBTAINED BY RUNNING FULL AC LOAD FLOW WITH VARIOUS EXPONENTS

Outage Line/Gen	VPI 2	VPI 10	VPI 20	Bus Voltage Status
Line No				
1	Load flow has not converged			
2	4.669034(3)	.27140E+01(5	.11265E+02(6)	V
3	7.711963(2)	.89302E+03(1)	.39303E+07(1)	V
4	1.908948(16)	.59594E-01(17)	.59248E-02(17)	NV
5	2.337227(10)	.21034E+00(11)	.10661E+00(11)	V
6	2.455002(9)	.14606E+00(12)	.35012E-01(12)	NV
7	2.080577(13)	.10101E+00(13)	.22385E-01(14)	NV
8	4.156054(4)	.19433E+02(3)	.12162E+04(3)	V
9	1.627647(20)	.34638E-01(20)	.24616E-02(20)	NV
10	2.116308(12)	.80009E-01(14)	.15793E-01(15)	NV
11	3.548775(6)	.20711E+01(6)	.12545E+02(5)	V
12	1.707918(19)	.76727E-01(15)	.23123E-01(13)	NV
13	2.334542(11)	.10257E+02(4)	.52537E+03(4)	V
14	3.143195(7)	.40340E+00(10)	.34086E+00(10)	V
15	1.996183(15)	.61130E-01(16)	.10723E-01(16)	NV
16	1.717426(18)	.41983E-01(19)	.58415E-02(18)	NV
17	2.747381(8)	.47540E+00(9)	.54846E+00(9)	V
18	1.723022(17)	.43081E-01(18)	.45938E-02(19)	NV
19	1.515521(21)	.25451E-01(21)	.15738E-02(21)	NV
20	2.070389(14)	.80783E+00(8)	.31501E+01(7)	V
Gen No				
2	3.806472(5)	.11270E+01(7)	.19539E+01(8)	V
3	8.371559(1)	.30097E+02(2)	.13856E+04(2)	V

Note V Violating
NV Non-Violating
Number given in parenthesis refers to the ranking.
VPI 2: Voltage Performance Index with exponent 2

TABLE-3.2a

COMPARISON OF QPIs OBTAINED BY FACTORS METHOD WITH VARIOUS EXPONENTS

Outage Line/Gen	QPI 2	QPI 10	QPI 20
Line No			
1	.58185E+01(3)	.59578E+03(3)	.90117E+06(3)
2	33621E+01(20)	.26116E+03(5)	.34058E+06(5)
3	61466E+01(2)	.15464E+05(2)	.11957E+10(2)
4	34911E+01(17)	.25833E+03(6)	.33305E+06(6)
5	34140E+01(19)	.26617E+03(4)	.35384E+06(4)
6	.35874E+01(7)	.25538E+03	.32553E+06
7	35878E+01(6)	.25538E+03	.32553E+06
8	37796E+01(5)	.25539E+03	.32553E+06
9	.69812E+01(1)	.23507E+05(1)	.27629E+10(1)
10	.34954E+01(16)	.25539E+03	.32553E+06
11	.35088E+01(14)	.25537E+03	.32553E+06
12	35232E+01(8)	.25539E+03	.32553E+06
13	35200E+01(11)	.25538E+03	.32553E+06
14	40846E+01(4)	.25572E+03(7)	.32553E+06
15	35131E+01(13)	.25538E+03	.32553E+06
16	35087E+01(15)	.25537E+03	.32553E+06
17	34790E+01(18)	.25661E+03	.32876E+06
18	.35212E+01(10)	.25539E+03	.32553E+06
19	.35231E+01(9)	.25539E+03	.32553E+06
20	.35185E+01(12)	.25538E+03	.32553E+06
Gen No			
2	.24997E+01(22)	.24871E+03	.30927E+06
3	.31546E+01(21)	.25454E+03	.32361E+06

Note: QPI 2= Reactive Power Performance Index with exponent 2.
Number given in parenthesis refers to the ranking.

TABLE 3.2b

COMPARISON OF QPIs OBTAINED AFTER RUNNING FULL AC LOAD FLOW WITH VARIOUS EXPONENTS

Line/Gen Outage	QPI 2	QPI 10	QPI 20
Line No			
1	50943E+01(02)	.34810E+04(02)	.60498E+08(02)
2	50507E+01(03)	.55241E+03(04)	.14538E+07(04)
3	70868E+01(01)	.20961E+05(01)	.21967E+10(01)
4	38001E+01(10)	.52152E+03(05)	.13596E+07(05)
5	41407E+01(06)	.91393E+03(03)	.41756E+07(03)
6	35835E+01(14)	.32191E+03(10)	.51725E+06(10)
7	35388E+01(17)	.26414E+03(14)	.34822E+06(14)
8	36125E+01(13)	.32755E+03(08)	.53550E+06(08)
9	20404E+01(22)	.67852E+01(22)	.13916E+03(22)
10	39925E+01(08)	.32646E+03(09)	.53199E+06(09)
11	39449E+01(07)	.28184E+03(13)	.39642E+06(13)
12	36318E+01(12)	.20804E+03(20)	.21598E+06(20)
13	36584E+01(11)	.20515E+03(21)	.21002E+06(21)
14	43213E+01(04)	.23672E+03(18)	.27596E+06(18)
*15	34935E+01(19)	.25255E+03(17)	.31831E+06(17)
16	34508E+01(20)	.22573E+03(19)	25430E+06(19)
17	41598E+01(05)	.49625E+03(06)	.12242E+07(06)
18	35497E+01(16)	.28612E+03(12)	.40862E+06(12)
19	35239E+01(18)	.25722E+03(16)	.33023E+06(16)
20	35563E+01(15)	.29494E+03(11)	.43421E+06(11)
Gen No			
2	51337E+01(21)	.26251E+03(15)	.34377E+06(15)
3	38100E+01(09)	.35596E+03(07)	.63140E+06(07)

Note QPI 2 = Reactive Performance Index obtained with exponent 2.

TABLE-3.3a

OPTIMAL WEIGHTS ASSOCIATED WITH BUS VOLTAGES

Bus No	Optimal Weight
2	.24341768E+11
3	-.80659984E+08
4	.69220720E+06
5	-.86221513E+13
6	-.87613909E+09
7	.57939656E+08
8	-.15597948E+05
9	-.13392826E+05
10	-.48777107E+07
11	.41619617E+08
12	-.12758524E+08
13	.47526336E+07
14	.22186640E+04

Note : Optimal weight associated with bus-1(slack) is insignificant as the voltage deviation is zero at slack.

TABLE-3.3b

OPTIMAL WEIGHTS ASSOCIATED WITH Q-SOURCES

Q-Source No	Optimal Weight
1	.43942874E+00
2	.95915733E+00
3	.82600796E+00
4	.49014612E+00
5	.56535445E+02

TABLE 3.4a

COMPARISON OF VPIs OBTAINED BY FACTORS METHOD USING THE OPTIMAL WEIGHTS WITH THAT OF FULL AC LOAD FLOW

Line/Gen outage	Factors method	AC load flow
Line No		
1	769.2601558927083	not converged
2	11.26542472915025	11.265376
3	930296.499956145	3930296.5
4	2.396176804481342E-02	5.9247940000000000E-03
5	.1042288454507342	.10661497
6	-.123387170798395	3.5011942999999999E-02
7	-8.967237402279959E-02	2.2384771000000000E-02
8	1216.206839859732	1216.1917
9	-7.97911719787953	2.4615746000000000E-03
10	5.119544230896732E-02	1.5792882000000000E-02
11	12.66541614815903	12.544927
12	-1.15279716961427	2.3123244000000000E-02
13	516.9864674322652	525.36812
14	.2381854488629256	.3408643
15	-2.07592603899705	1.0723263000000000E-02
16	.7725866222321227	5.8414716000000000E-03
17	1.00716034691231	.54846344
18	1.15277060416016	4.5937617000000000E-03
19	2.31509199488985	1.5737640000000000E-03
20	67.990316431517	3.1501054
Gen No		
2	1.95387060800567	1.95387063
3	1385.563001535832	1385.563

TABLE 3.4b
COMPARISON OF QPIs OBTAINED BY FACTORS METHOD USING THE OPTIMAL WEIGHTS WITH THAT OF FULL AC LOAD FLOW

Line/Gen outage	AC Load Flow	Factors method
Line No		
1	5.81846920885382	5.6943
2	3.36214739474536	5.0507
3	6.14659428889309	7.0868
4	3.49112064753459	3.8001
5	3.41403665125746	4.1407
6	3.58737739914148	3.5885
7	3.58780988724758	3.5388
8	3.77959992436361	3.6125
9	6.981238911712	2.6404
10	3.49541131742889	3.8925
11	3.5087966387337	3.9449
12	3.52319658549863	3.6318
13	3.5200317172085	3.6584
14	4.08460713161825	4.3213
15	3.51308490259124	3.4935
16	3.50872584963889	3.4508
17	3.47901235320295	4.1588
18	3.5212170928574	3.5497
19	3.52305483743249	3.5239
20	3.51846493534591	3.5563
Gen No		
2	2.49966072210234	3.1337
3	3.15461951397959	3.81

TABLE-3.5a

COMPARISON OF VPIs OBTAINED BY FACTORS METHOD
WITH VARIOUS EXPONENTS

Voltage Line/Gen	VPI 2	VPI 10	VPI 20	Bus Voltage Status
Line No.				
1	.32287E+02	.13521E+05	.17651E+09	
2	.19162E+02	.10612E+04	.13232E+07	
3	.15240E+02	.34023E+03	.14394E+06	
4	.66576E+01	.74292E+01	.10309E+03	
5	.22274E+01(14)	.51812E-01(14)	.58472E-02(14)	NV
6	.19992E+03(03)	.88402E+08(03)	.80166E+16(02)	V
7	76407E+03(01)	.73101E+11(01)	.56254E+22(01)	V
8	.20282E+01(15)	.31247E-01(15)	.20670E-02(15)	NV
9	.24471E+01(13)	.81771E-01(13)	.15159E-01(13)	NV
10	.52046E+02(05)	.12975E+06(05)	.16585E+11(05)	V
11	.13211E+02(10)	.19519E+03(10)	.67411E+05(10)	NV
12	73741E+02(04)	.67069E+06(04)	.42716E+12(04)	V
13	35372E+02(07)	.17560E+05(07)	.43765E+09(07)	V
14	.20577E+03(02)	.93855E+08(02)	.76386E+16(03)	V
15	.18624E+03	.41502E+08	.24570E+16	
16	.28497E+02(08)	.94185E+04(08)	.21044E+09(08)	V
17	.35623E+02(06)	.26019E+05(06)	.16015E+10(06)	V
18	.19439E+02(09)	.16676E+04(09)	.66885E+07(09)	V
19	.24275E+03	.13955E+09	.28274E+17	
20	.16851E+03	.36289E+08	.13205E+16	
21	.20307E+01	.29660E-01	.17461E-02	
22	.11163E+03	.50967E+07	.33818E+14	
23	.68500E+02	.68113E+06	.63651E+12	
24	.35520E+01	.67213E+00	.10610E+01	
Gen No.				
2	.22719E+02	.23542E+04	.57747E+07	
3	.92881E+01(11)	.43235E+02(11	.32297E+04(11)	NV
4	.43062E+01(12)	.13896E+01(12)	.43890E+01(12)	NV

Note: V : Violating
NV: Non-Violating
Number given in pranthesis refers to ranking.
VPI 2: Voltage Performance Index with exponent 2

TABLE 3.5b

COMPARISON OF VPIs OBTAINED BY RUNNING FULL AC LOAD FLOW WITH VARIOUS EXPONENTS

uutage .ine/Gen	VPI 2	VPI 10	VPI 20	Bu Vc St
.ine No.				
5	.5707224E+01(09)	.2550402E+01(10)	.1027489E+02(10)	N
6	.1943457E+04(02)	.2852177E+13(02)	.6271153E+25(02)	
7	.1291798E+03(04)	.2627690E+07(04)	.4371730E+13(04)	
8	.1388364E+01(15)	.5975432E-02(14)	.8796558E-04(13)	N
9	.2429371E+01(12)	.5731252E-01(12)	.8015052E-02(12)	N
10	.2478646E+02(06)	.1313027E+05(06)	.4138272E+09(06)	
11	.1983028E+01(13)	.9401519E-02(13)	.7152308E-04(14)	N
12	.5592239E+02(05)	.1253012E+06(05)	.1832864E+11(05)	
13	.5360941E+04(01)	.6149688E+15(01)	.3315693E+30(01)	
14	.1610369E+04(03)	.1132791E+13(03)	.9573743E+24(03)	
16	.5627973E+01(10)	.1182842E+02(09)	.3595399E+03(09)	N
17	.8662158E+01(08)	.1282099E+03(08)	.2060990E+05(08)	N
18	.3426267E+01(11)	.3704335E+00(11)	.5060231E+00(11)	N
... No.				
3	.1482296E+01(14)	.3672532E-02(15)	.1189609E-04(15)	N
4	.2180394E+02(07)	.2566990E+04(07)	.7452152E+07(07)	

TABLE-3.6a

COMPARISON OF QPIs OBTAINED BY FACTORS METHOD WITH VARIOUS EXPONENTS

Outage Line/Gen	QPI 2	QPI 10	QPI 20
Line No.			
1	.48088E+02	.70779E+09	.25048E+19
2	.22395E+01	.12253E+01	.48179E+01
3	.20405E+02	.78818E+07	.31061E+15
4	.53626E+01	.30364E+04	.46091E+08
5	.14874E+01(09)	.25477E+00	.10821E+00
6	.49130E+03	.90251E+14	.40726E+29
7	.19930E+04	.10026E+18	.50263E+35
8	.16285E+01(08)	.25532E+00(08)	.10821E+00
9	.14640E+01(10)	.25477E+00	.10821E+00
0	.97199E+02(02)	.25750E+11(02)	.33152E+22(02)
1	.18324E+02(06)	.43759E+07(06)	.95742E+14(06)
2	.14440E+03	.19102E+12	.18245E+24
3	.71585E+02	.54297E+10	.14741E+21
4	.50182E+03	.10037E+15	.50372E+29
5	.55247E+03	.16255E+15	.13210E+30
6	.83787E+02(03)	.12108E+11(03)	.73306E+21(03)
17	.11256E+03(01)	.54179E+11(01)	.14677E+23(01)
18	.51770E+02(05)	.10322E+10(05)	.53275E+19(05)
19	.77966E+03	.91336E+15	.41711E+31
20	.37526E+03	.23355E+14	.27274E+28
21	.14545E+01	.25477E+00	.10821E+00
22	.31332E+03	.94402E+13	.44559E+27
23	.21672E+03	.14794E+13	.10944E+26
24	.32876E+01	.66995E+02	.22271E+05
Gen No.			
2	.79490E+02(04)	.95533E+10(04)	.45632E+21(04)
3	.17070E+02	.34638E+07	.59989E+14
4	.17076E+02(07)	.34638E+07(07)	.59989E+14(07)

TABLE 3.6b

COMPARISON OF QPIs OBTAINED AFTER RUNNING FULL AC LOAD FLOW WITH VARIOUS EXPONENTS

Line/Gen Outage	QPI 2	QPI 10	QPI 20
Line No.			
5	.15104E+02(03)	.15645E+07(03)	.12239E+14(03)
8	.21288E+01(09)	.72681E+00(09)	.12438E+01(09)
9	.19716E+01(10)	.38620E+00(10)	.20632E+00(10)
10	.27178E+02(02)	.36868E+08(02)	.67964E+16(02)
11	.49152E+01(07)	.16755E+04(07)	.14033E+08(07)
16	.56092E+01(06)	.42083E+04(06)	.88538E+08(06)
17	.67775E+01(04)	.14446E+05(04)	.10433E+10(04)
18	.43534E+01(08)	.70137E+03(08)	.24580E+07(08)
Gen No.			
2	.14238E+03(01)	.18140E+12(01)	.16452E+24(01)
4	.60152E+01(05)	.10524E+05(05)	.55374E+09(05)

CHAPTER - 4

CONCLUSIONS

Power system security monitoring and analysis forms an integral part of the modern energy management system (EMS) but its on-line implementation poses a major challenge to the power system engineers. Recently the voltage security problem has found more attention by researchers. Contingency selection is performed to minimize the total number of contingencies to be analyzed by full AC load flow and hence reducing the total time of security analysis. From the available literature on voltage contingency selection, it is observed that further improvements are needed in the available methods,

a) to adopt better performance indices which can truly reflect the relative severity of the contingency cases; thus minimizing the misranking and masking effects, inherent with existing second order performance indices

b) to explore faster and more accurate models for predicting the post outage voltages and reactive powers for all contingencies before ranking.

Keeping the above two objectives in mind, in the present thesis a new set of voltage and reactive power distribution factors have been suggested, which can be directly obtained from a base case load flow results using sensitivity properties of N.R.

load flow Jacobians. Higher order voltage and reactive power performance indices have been tried out and a new approach for finding optimal weights used in the performance indices, based on least square error method, has been suggested. System studies to test the effectiveness of the new distribution factors and the performance indices, were conducted on IEEE-14 bus and a 19-bus Indian system (representing UP State 400 kV transmission network). Following main conclusions can be drawn from the works reported in this thesis:-

1) The proposed voltage distribution factors predict the bus voltages with sufficient accuracy. However, the proposed reactive power distribution factors are not equally accurate in predicting the reactive power outputs of sources.

2) The calculation of distribution factors and ~~its~~ their updating is extremely fast as it utilizes only the available base load flow results. For slight variation in loading (upto ± 5%) the factors need not be updated and the one already computed can be used for predicting the bus voltages. This further reduces the computational time for security analysis.

3) Use of higher order voltage performance indices eliminates the problem of masking effct. An exponent of 20 or more should be used in the voltage performance index. However, use of higher exponents in reactive power performance index do not significantly affect the relative ranking of contingencies.

4) Use of the optimal weights obtained through the proposed LSE method in the voltage as well as reactive power performance indices brings their values computed by the distribution factors method and the exact methods quite close. Thus, it minimizes the misranking effect.

5) For voltage contingency selection, it is recommended to use the proposed voltage performance index algorithm alongwith the suggested voltage distribution factors for post outage voltage prediction. This model is found to be superior to the reactive power performance index based model utilizing the reactive power distribution factors. The voltage contingency selection algorithm, so obtained, will be extremely fast and can be effectively used for real time voltage security analysis.

As a consequence of the works carried out in this thesis, further research efforts can be made in the following direction :

i) The distribution factors suggested in this thesis have been derived for only a single outage of line/transformer or generator. The distribution factors, on similar lines, can be explored for multiple contingencies.

ii) The reactive power based ranking has not been found effective in the present work. Further investigations are required to evolve better models. A hybrid performance index considering both bus voltages and reactive powers can also be tried out.

iii) The studies have been conducted on only 14-bus and 19-bus systems. It can be tried out on larger practical systems containing several hundred buses and lines.

iv) Recently neural networks have been popularly used for various power system studies. Being non-algorithmic in nature and extremely fast, it is ideally suited for security analysis problems. The neural network based models for the contingency selection and analysis can be tried out.

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APPENDIX-A

DATA FOR IEEE-14 BUS SYSTEM (100 MVA BASE)

The IEEE-14 bus network is shown in fig-A.

Table-A.1
(Generator Bus Data)

Bus no	Scheduled real power generation Pg(MW)	Specified voltage magnitude (p.u.) Vspe	Reactive generation limit Max(MVAR)	Min(MVAR)
1	--	1.060	--	--
2	40.0	1.045	0.5	-0.4
3	20.0	1.070	0.24	-0.06
4	0.0	1.010	0.4	-0.0
5	0.0	1.090	0.24	-0.06

Real and reactive power load at generator buses are zero.

Table-A.2
(Load Bus Data)

Bus no	Load Real(MW)	Reactive(MVAR)	External shunt susceptance (p.u.)
6	0.0	0.0	0.0
7	29.5	16.6	0.19
8	7.6	1.6	0.0
9	47.8	3.9	0.0
10	9.0	5.8	0.0
11	3.5	1.8	0.0
12	6.1	1.6	0.0
13	13.5	5.8	0.0
14	14.9	5.0	0.0

Table-A.3

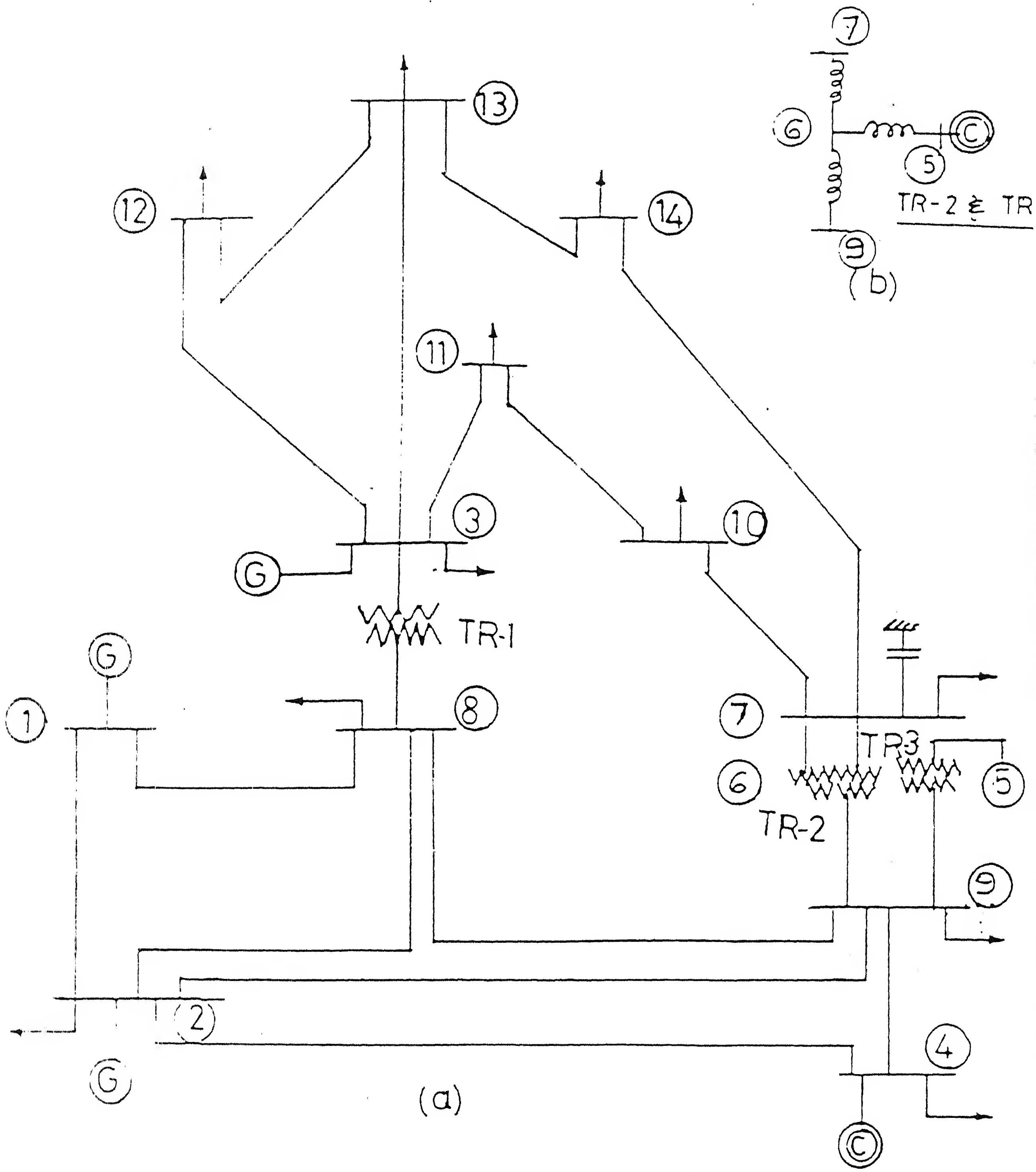
(Transformer Data)

Bus no	From bus	To bus	Series impedance R (p.u.)	Series impedance X (p.u.)	Tap setting
14	8	3	0.0	.25202	0.962
15	9	6	0.0	.20912	0.978
16	9	7	0.0	.55618	0.969

Table-A.4

(Line Data)

Bus no	From bus	To bus	Series impedance R (p.u.)	Series impedance X (p.u.)	Shunt susceptance B(p.u.)
1	1	2	.01938	.05917	.0264
2	1	8	.05403	.22304	.0246
3	2	4	.04699	.19797	.0219
4	2	8	.05695	.17388	.017
5	2	9	.05811	.17632	.0187
6	3	11	.09498	.19890	.0000
7	3	12	.12291	.25581	.0000
8	3	13	.06615	.13027	.0000
9	4	9	.06701	.17103	.0173
10	6	5	.00000	.17615	.0000
11	6	7	.00000	.11001	.0000
12	7	10	.03181	.08450	.0000
13	7	14	.12711	.27038	.0000
17	9	8	.01335	.04211	.00640
18	10	11	.08205	.19207	.00000
19	2	13	.22092	.19988	.00000
20	13	14	.17093	.34802	.00000



G GENERATOR

C SYNCHRONOUS CONDENSER

SHUNT REACTOR/ CAPACITOR

TRANSFORMER

FIG. A IEEE-14 BUS SYSTEM

(BUSES RENUMBERED)

ONE LINE DIAGRAM

3-WINDING TRANSFORMER EQUIVALENT

APPENDIX-B

DATA FOR UPSEB 400KV-19 BUS SYSTEM (100 MVA BASE)

The UPSEB 400KV-19 bus network is shown in fig-B.

Table-B.1

(Generator Bus Data)

Bus no	Scheduled real power generation Pg(MW)	Specified voltage magnitude (p.u.) Vspe	Reactive generation limit Max(MVAR)	Reactive generation limit Min(MVAR)
1	--	1.03	--	--
2	1600.0	1.03	144.0	0.0
3	900.0	1.03	80.0	0.0
4	550.0	1.03	50.0	0.0

Real and reactive power load at generator buses are zero.

Table-B.2
(Load Bus Data)

Bus no	Load Real(MW)	Load Reactive(MVAR)	External shunt reactance (p.u.)
5	0.0	0.0	.494395
6	191.0	16.0	1.10250
7	1000.0	0.0	1.75000
8	0.0	0.0	2.20500
9	135.0	78.0	2.20500
10	236.0	45.0	2.20500
11	360.0	11.0	.676380
12	337.0	59.0	2.20500
13	90.0	20.0	0.00000
14	520.0	84.0	2.20500
15	387.0	64.0	1.10250
16	288.0	0.0	0.40384
17	477.0	00.0	2.20500
18	-151.0	69.0	0.00000
19	-263.0	00.0	0.00000

Table-B.3
(Transformer Data)

Bus no	From bus	To bus	Series impedance R (p.u.)	Series impedance X (p.u.)	Tap setting
1	5	2	.00016	.00591	1.000
2	6	1	.00073	.01460	1.000
3	7	3	.00030	.01199	1.000
4	8	4	.00049	.01943	1.000

Table-B.4
(Line Data)

Bus no	From bus	To bus	Series impedance R (p.u.)	Series impedance X (p.u.)	Shunt susceptance B(p.u.)
5	5	7	.00031	.00310	.04056
6	7	16	.00918	.09306	1.21680
7	16	5	.00439	.04464	2.34148
8	8	5	.00031	.00310	.04056
9	6	8	.00051	.00517	.06760
10	8	9	.00479	.04880	.63614
11	10	9	.00254	.02584	.33798
12	6	10	.00468	.04770	.62450
13	10	11	.00294	.02997	.39206
14	11	5	.00823	.08375	1.09503
15	11	12	.00650	.06617	.86521
16	13	12	.00325	.03307	.43264
17	13	14	.00370	.03762	.48870
18	14	12	.00260	.02646	.34610
19	15	14	.00806	.08169	1.06808

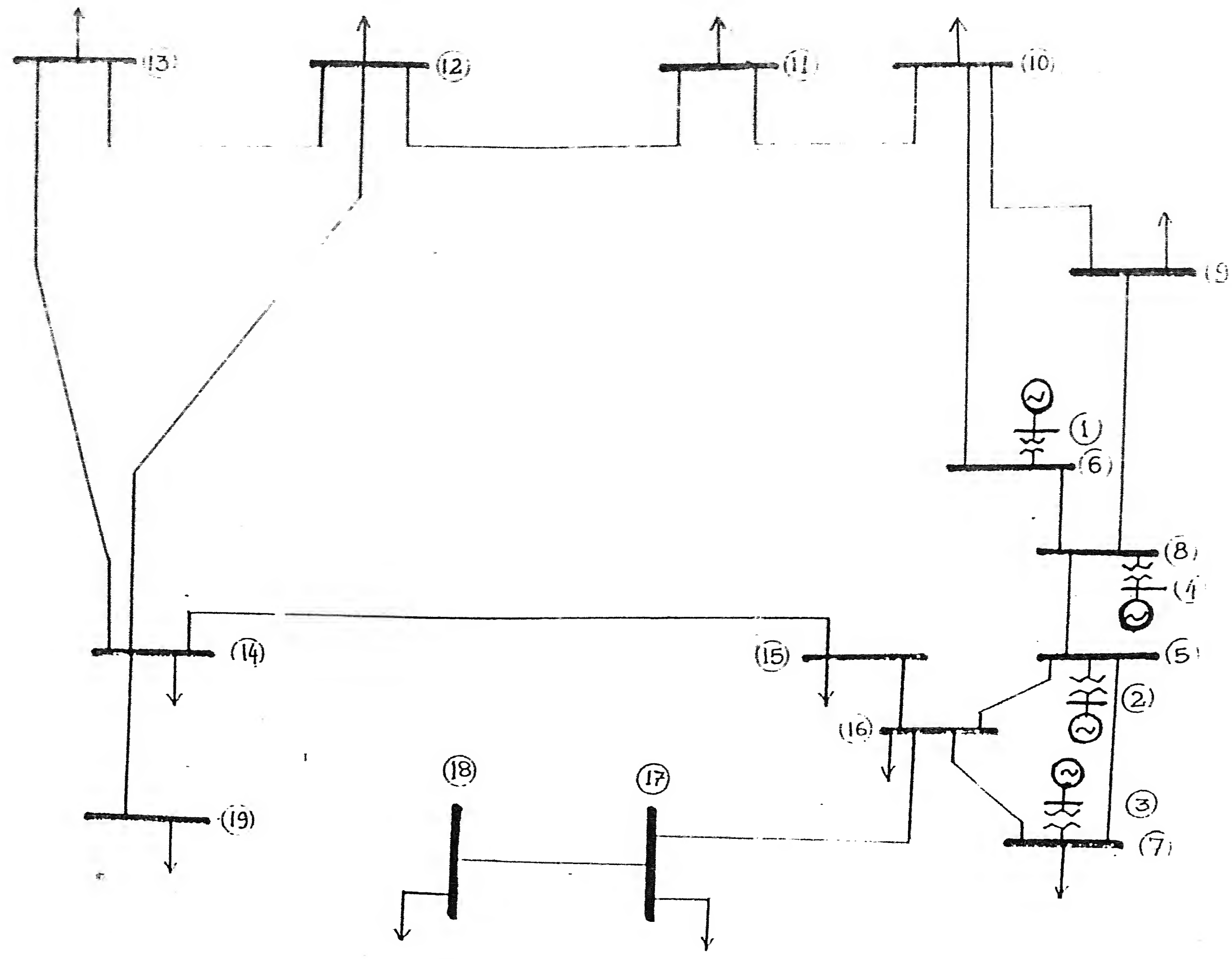


Fig.B 19 - Bus Indian system.